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STS-73 (USML-2) Final Report

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1.0 INTRODUCTION

The report is organized into sections representing the phases of work performed in analyzing the STS-73 (USML-2) results. Section 1 briefly outlines the OARE system features, coordinates, and measurement parameters. Section 2 describes the results from STS-73. The mission description, data calibration, and representative data obtained on STS-73 are presented. Also, the anomalous performance of OARE on STS-73 is discussed. Finally, Section 3 presents a discussion of accuracy achieved and achievable with OARE.

1.1 OARE System Features

The Orbital Acceleration Research Experiment (OARE) contains a tri-axial accelerometer which uses a single free-floating (non-pendulous) electrostatically suspended cylindrical proofmass. The accelerometer sensor assembly is mounted to a microprocessor-controlled, dual-gimbal platform in order to perform in-flight calibrations. Acceleration measurements are processed and stored in the OARE flight computer memory and, simultaneously, the unprocessed data are recorded on the shuttle payload tape. The payload tape recorder data are telemetered periodically to ground stations at several hour intervals during flight via tape recorder playback (data dumps). On STS-73 the OARE data stream was routed through USML-2 and the OARE data were telemetered to NASA receiving stations in real time for the first time.

OARE's objectives are to measure quasi-steady accelerations, to make high resolution low-frequency acceleration measurements in support of the micro-gravity community, and to measure Orbiter aerodynamic performance on orbit and during reentry. There are several features which make the OARE desirable for making highly accurate, low-frequency acceleration measurements. OARE is the first high resolution, high accuracy accelerometer flight design which has the capability to perform both bias and scale factor calibrations in orbit. Another design feature is the OARE sensor electrostatic suspension which has much less bias temperature sensitivity than pendulous accelerometers. Given the nature of the OARE sensor and its in-flight calibration capability, OARE stands alone in its ability to characterize the low-frequency environment of the Orbiter with less than 10 nano-g resolution and approximately 50 nano-g on-orbit accuracy.

1.2 Coordinate Systems

Two coordinate systems are used in this report -- the OARE axes centered at the OARE sensor proofmass centroid and the Orbiter aircraft body axes centered at the Orbiter's center of gravity. The direction from tail to nose of the orbiter is +X in both systems. The direction from port wing to starboard wing is +Z in the OARE system and +Y in the Orbiter system. The direction from the Orbiter belly to the top of the Orbiter fuselage is +Y in the OARE system and -Z in the Orbiter system. This sensor-to-body coordinate alignment is referred to as the nominal flight alignment and was utilized for OARE data collection during STS-73.

In discussions of OARE calibrations of bias and scale factor, the OARE reference system is used. Flight acceleration data are given in the Orbiter body reference system. The sign convention is such that when there is a forward acceleration of the Orbiter (such as the OMS firing), this is then reported as a positive X-axis acceleration. All accelerations given in this report refer to the OARE location.

1.3 Sensor Measurement Parameters 3 Sensor Measurement Parameters”

There are three sensor ranges, A, B, and C, for each OARE axis, which are controlled by auto-ranging software logic. The full scale ranges and resolutions (corresponding to one count) are given in Table 1. In any case where the sensor channel is driven into saturation, the output is set to 1.5 times full scale of range A with the sign of the saturation signal included.

Table 1. OARE Sensor Ranges and Resolutions

	Nominal Full Scale Range in micro-Gs	
Range	X-Axis	Y & Z Axes
A	10,000	25,000
B	1,000	1,970
C	100	150
	Resolution in nano-Gs SF_N in nano-Gs/count	
Range	X-Axis	Y & Z Axes
A	305.2	762.9
B	30.52	60.12
C	3.052	4.578

2.0 STS-73 (USML-2) MISSION RESULTS

This section describes the results from STS-73 as derived from post-flight analyses of the on-board stored EEPROM processed data. During the mission, preliminary calibrations and accelerations were reported in near-real time by Lewis Research Center with calibration support from Canopus Systems.

2.1 STS-73 (USML-2) Mission Plan

The STS-73 adaptation parameters anticipated a mission of up to 17 days long. In order to make better use of the calibration time, the software was modified so that only C-range calibrations would occur in the "Quiet" mode, and calibrations would occur on all three ranges during the "Normal" mode. Since past experience had indicated that the Scale Factor had minimal variations and that, on-orbit, the instrument remains almost entirely in the C-range, the adaptation parameters were selected to use most of the allotted calibration time for C-range bias calibrations in order to obtain the most accurate measurements possible. When operating in the "Quiet" mode, C-range bias calibrations were performed every 125 minutes, but a bias calibration began within one minute after the "Quiet" mode was asserted. A C-range scale factor calibration was performed after every 6th bias calibration in the "Quiet" mode. In the "Normal" mode, a full bias calibration was performed every 251 minutes, and a full scale factor calibration performed after every 3rd bias calibration. The calibration plan was to assert the "Quiet" mode when a quiet period could be anticipated. The STS-73 plan did not include any predefined "Quiet" periods in that "around the clock" astronaut operations were planned.

During STS-73, 170 C-range bias measurements were made. Fourteen bias measurements were made on the A and B ranges. There were 28 and 5 scale factor measurements made on the C and A&B ranges, respectively.

2.2 STS-73 Actual Mission Description

Launch for STS-73 was at 8:53 a.m. CDT on 20 October 1995. The actual length of the OARE STS-73 mission was nearly 16 days with touch down at 5:45 a.m. CST on 5 November 1995. Shutdown occurred in REENTER mode under the condition of "re-capture duration error" in sub-mode 4. This means that the OARE instrument continued to collect data until the Y-axis signal was saturated for at least 2 minutes in the final REENTER sub-mode. This is considered normal termination of the mission and represents adequate adaptation parameter settings for the reenter file size and correct timing of the reenter discrete.

All engineering parameter values were within normal range. Hardware performance was normal.

2.3 STS-73 Data Analysis

This section treats the several analyses carried out on the STS-73 flight data and summarizes the significant results. The processed acceleration data and the EEPROM files have already been delivered to the Microgravity Measurements and Analysis Branch at NASA Lewis Research Center.

The Orbital Acceleration Research Experiment (OARE) is designed to measure quasi-steady accelerations from below 10 nano-g up to 25 milli-g where quasi-steady indicates the frequency range from 10^{-5} to 10^{-1} Hz. To accomplish this, the sensor output acceleration signal is filtered with a Bessel filter with a cut-off frequency of 1 Hz. The output signal is digitized at 10 samples per second and is then further processed and digitally filtered onboard the OARE instrument with an adaptive trimmean filter prior to EEPROM storage and telemetry. The trimmean data samples cover 50 second periods every 25 seconds.

In flight, the OARE instrument is subjected to higher amplitude and higher frequency accelerations (such as structural vibration and crew noise effects) in addition to the quasi-steady accelerations such as those due to gravity gradient and on-orbit drag. However, these higher accelerations are not well characterized nor statistically invariant over the OARE measurement periods.

In order to obtain the optimum estimate of the quasi-steady acceleration under these conditions, a robust adaptive estimator has been implemented. The particular estimator used is known as the Hogg Adaptive Trimmean estimator and is described in Appendix A. The bias estimate of the accelerometer is critical to the accuracy of acceleration measurements. A detailed discussion of the data analysis undertaken for STS-73 is presented in Appendix A, with particular emphasis on bias estimated measurement errors based upon the distributions of the measured data. This mission incorporated a full weighted least squares estimate of bias for the first time.

The data analyzed and presented in this report are primarily those which were recorded on-board and have been processed by the on-board trimmean filter in 50 second periods. The acceleration data presented in this report, as well as the telemetry data at 10 samples per second which have not been processed by the trimmean filter, are available from the Microgravity Measurements and Analysis Branch at NASA Lewis Research Center.

The temperature environment was relatively benign after the initial thermal pulse generated during launch on STS-73. The instrument temperature in degrees Celsius (measured on the proofmass housing) is shown in Figure 1.

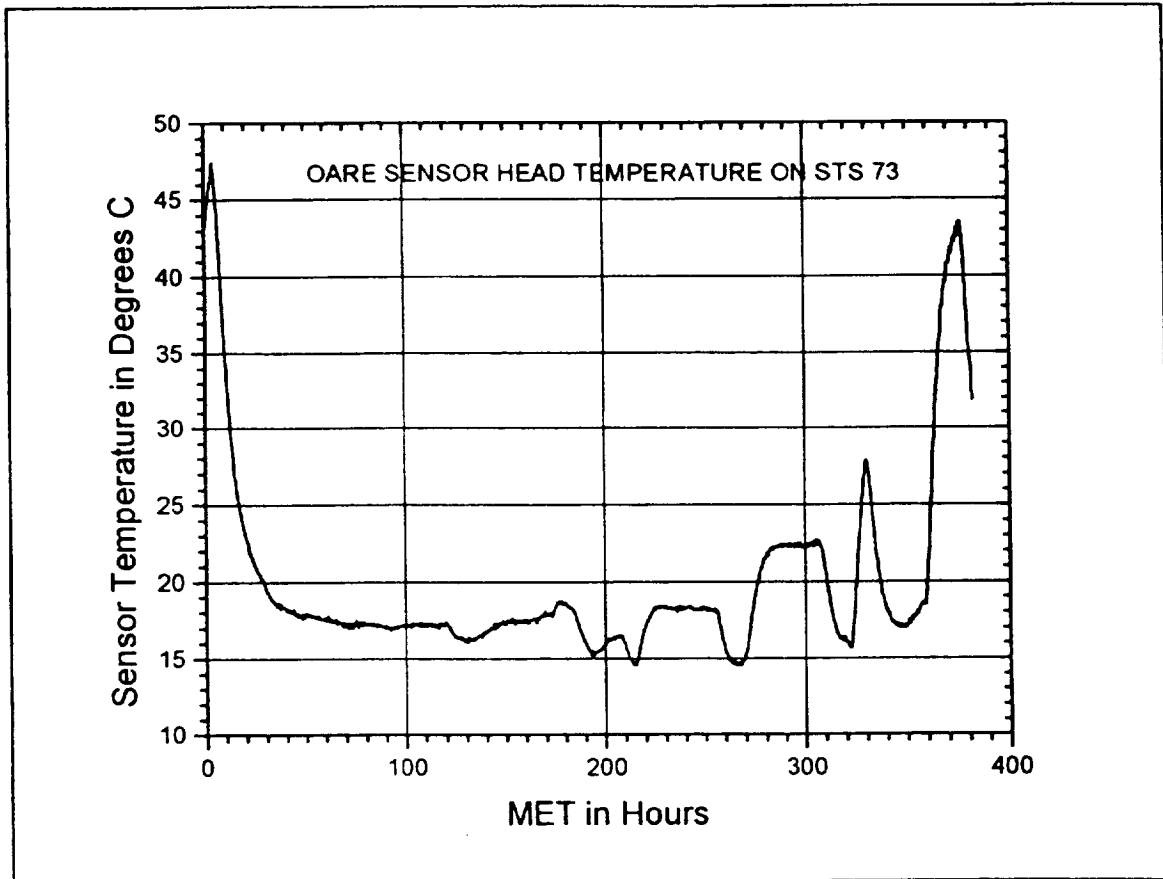


Figure 1. STS-73 Instrument (Sensor Head) Temperature

2.4 Orbiter Body Axis Acceleration Results.

The accelerations measured by OARE at the OARE location in the Shuttle Body Axes coordinate system (X- toward nose, Y -toward the starboard wing, Z -down through the belly) are shown in Figures 2-5 for representative time periods. Figures 2a, 2b, 2c, and 2d show the acceleration during the entire mission in segments of 96 hours. Figure 3 shows the induced acceleration at the OARE location during Orbiter maneuvers. Figure 4 shows a typical period from 72 to 98 hours at higher resolution at the standard 50-second trimmean averages at 25 second intervals. Figure 5 shows the same series of data when averaged over 10 minutes, but still at 25-second intervals, in order to better show the quasi-steady effects of the orbital period variations.

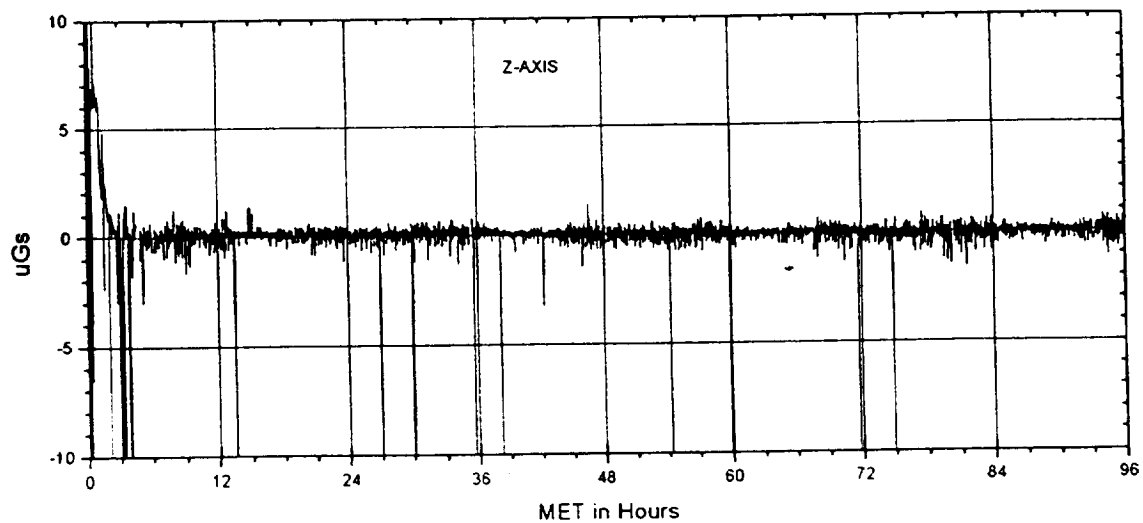
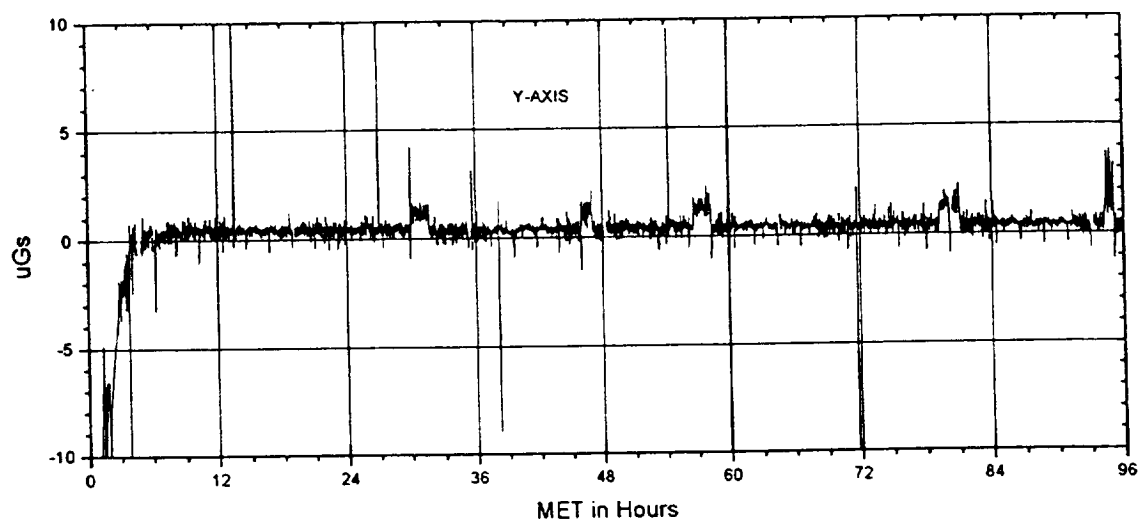
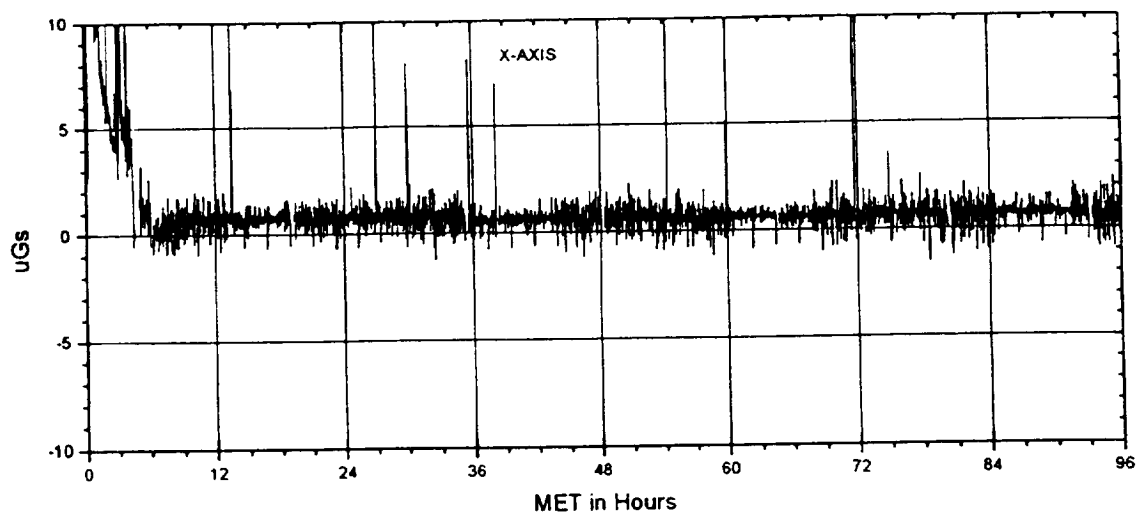


Figure 2a. Acceleration at the OARE location in Orbiter coordinates for MET 0-96 hours.

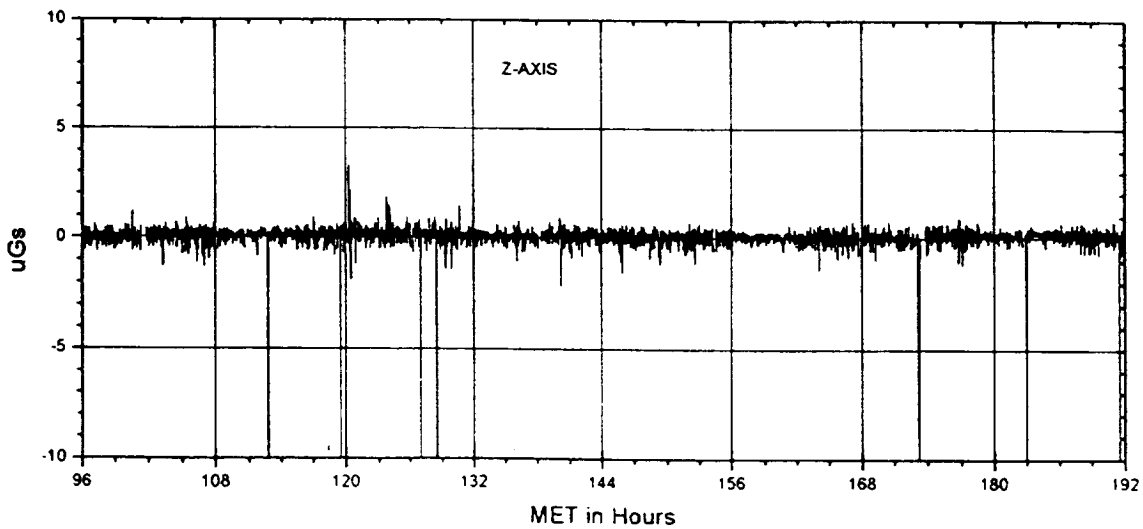
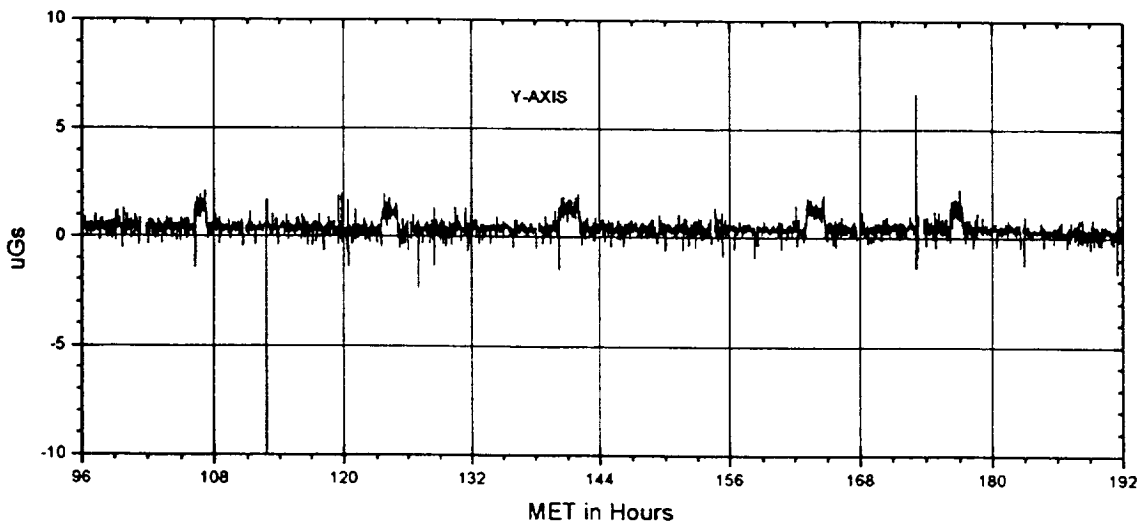
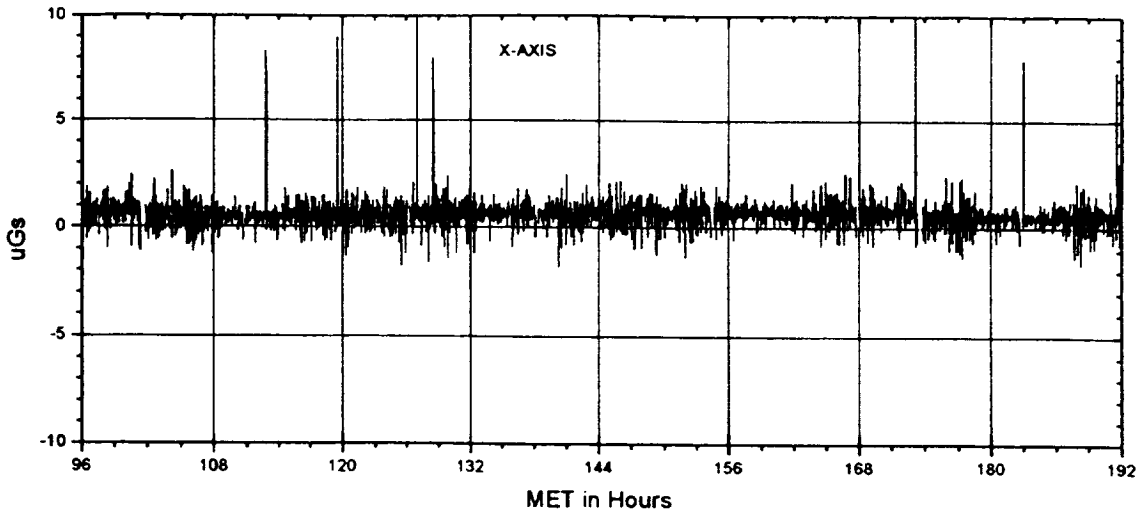


Figure 2b. Acceleration at the OARE location in Orbiter coordinates for MET 96-192 hours.

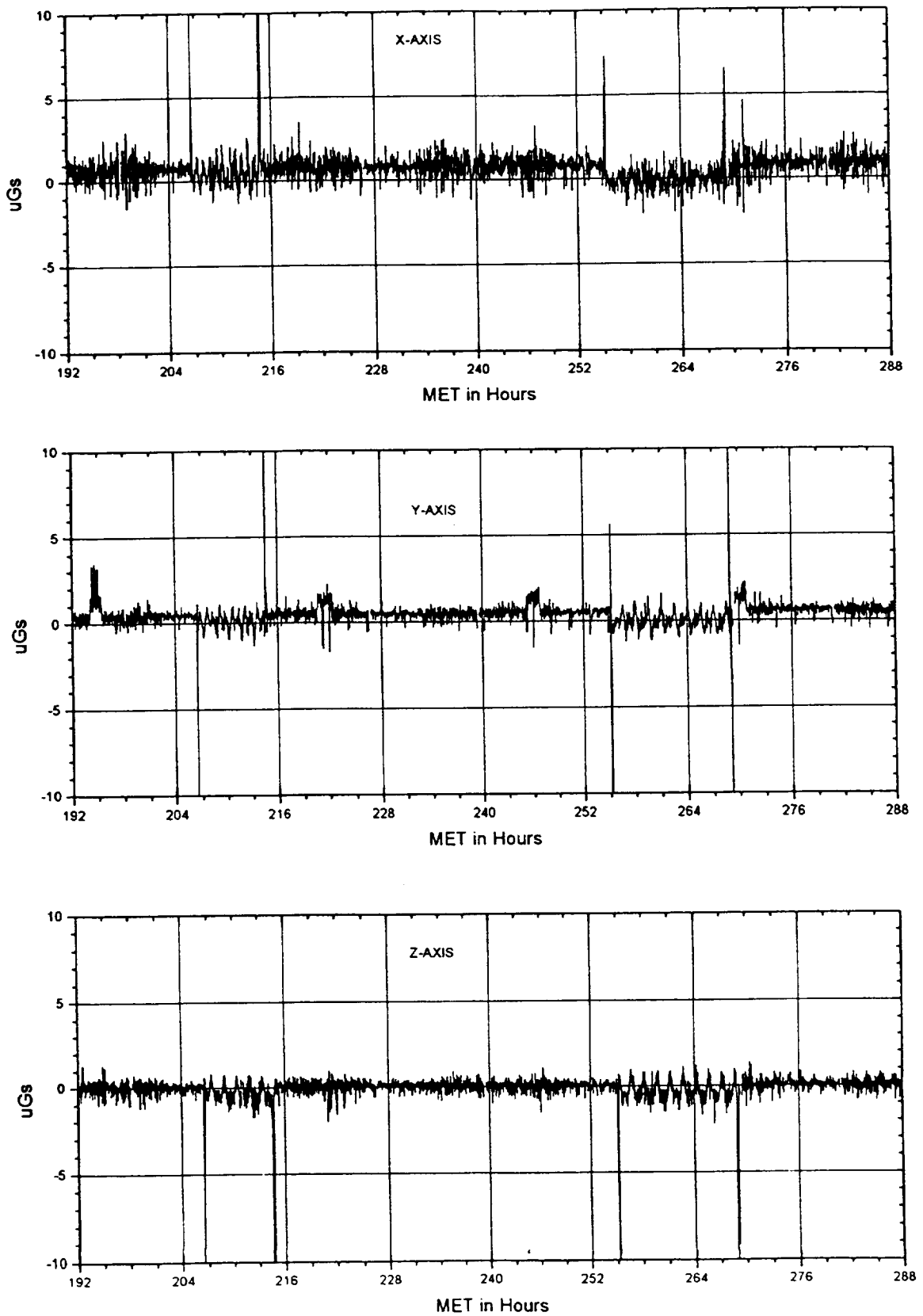


Figure 2c. Acceleration at the OARE location in Orbiter coordinates for MET 192-288 hours.

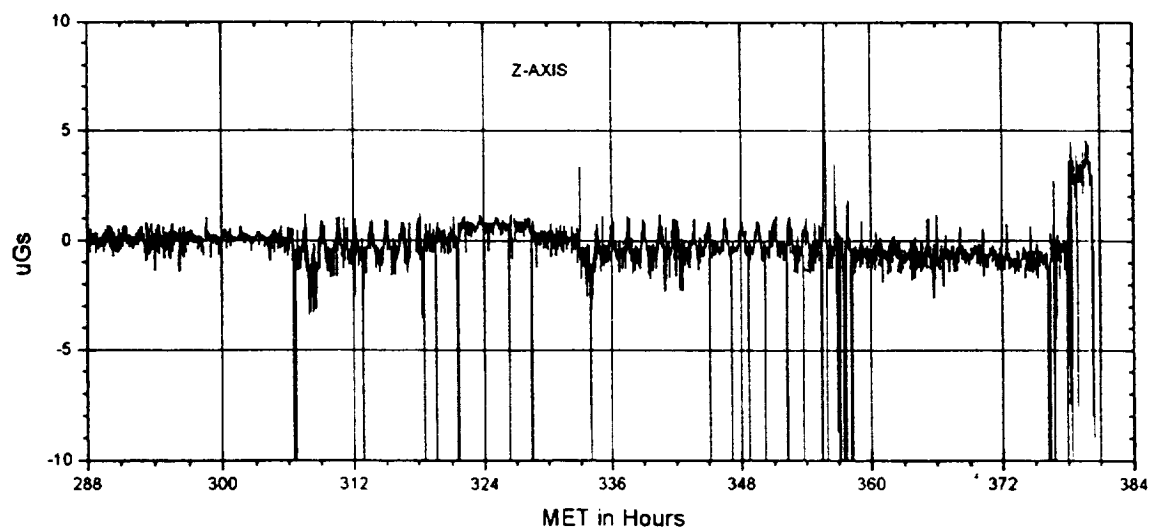
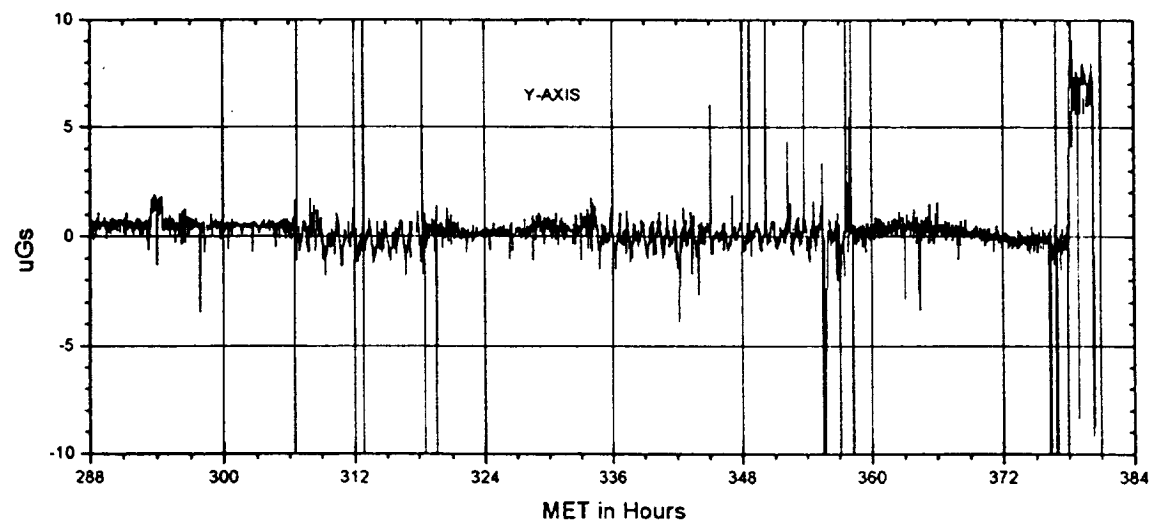
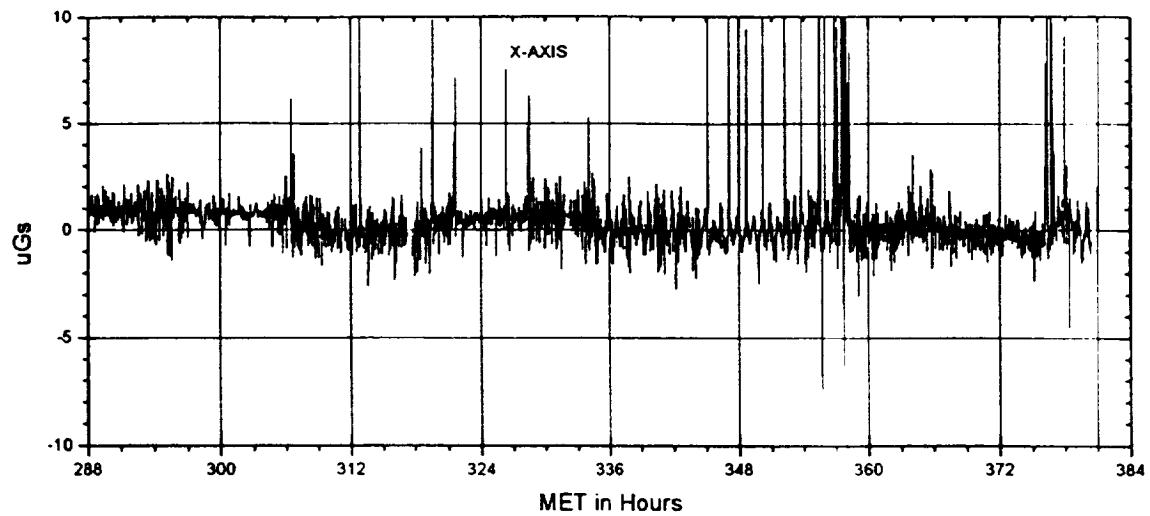


Figure 2d. Acceleration at the OARE location in Orbiter coordinates for MET 288-384 hours.

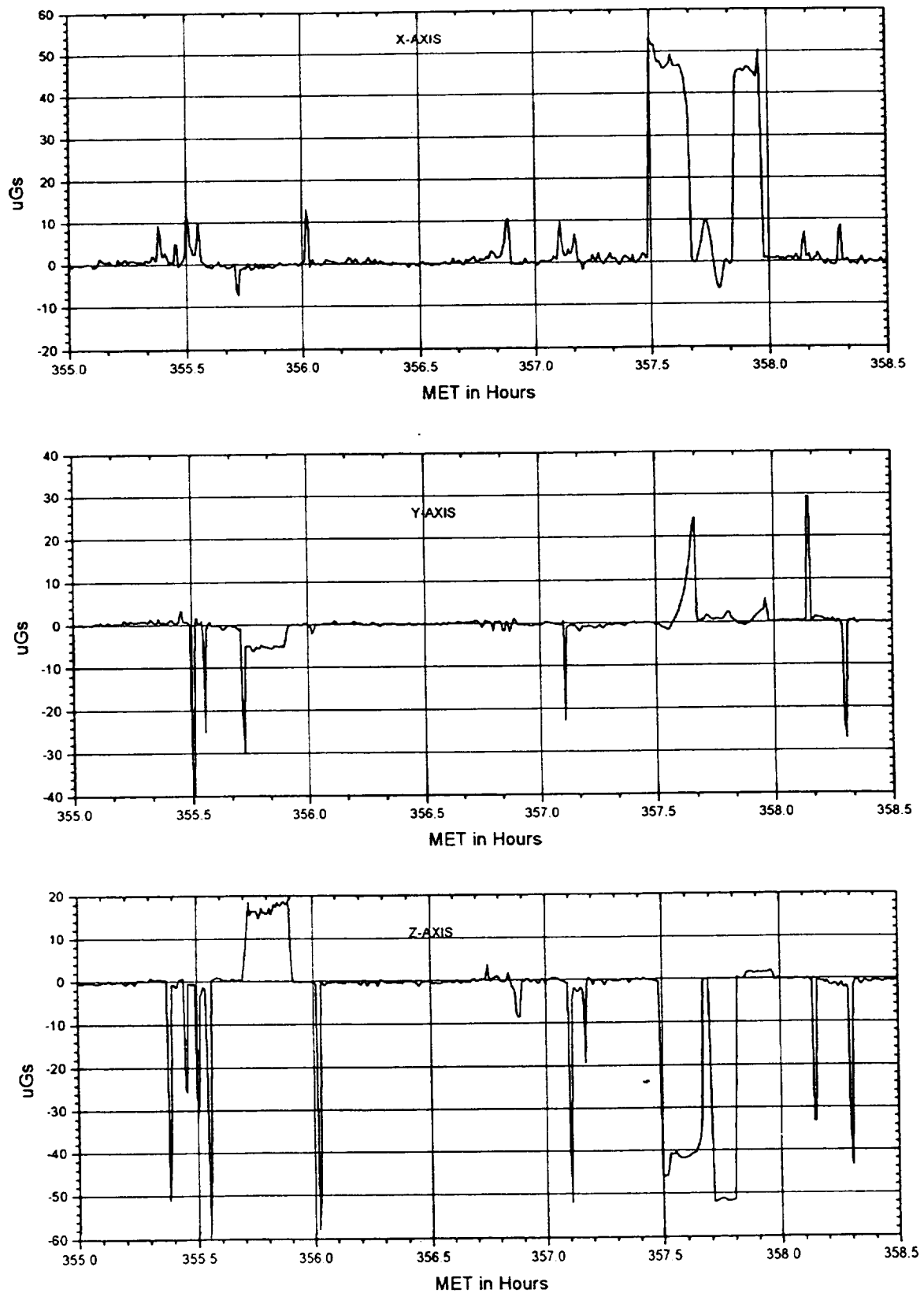


Figure 3. OARE acceleration measurements during SAMS calibration maneuvers.

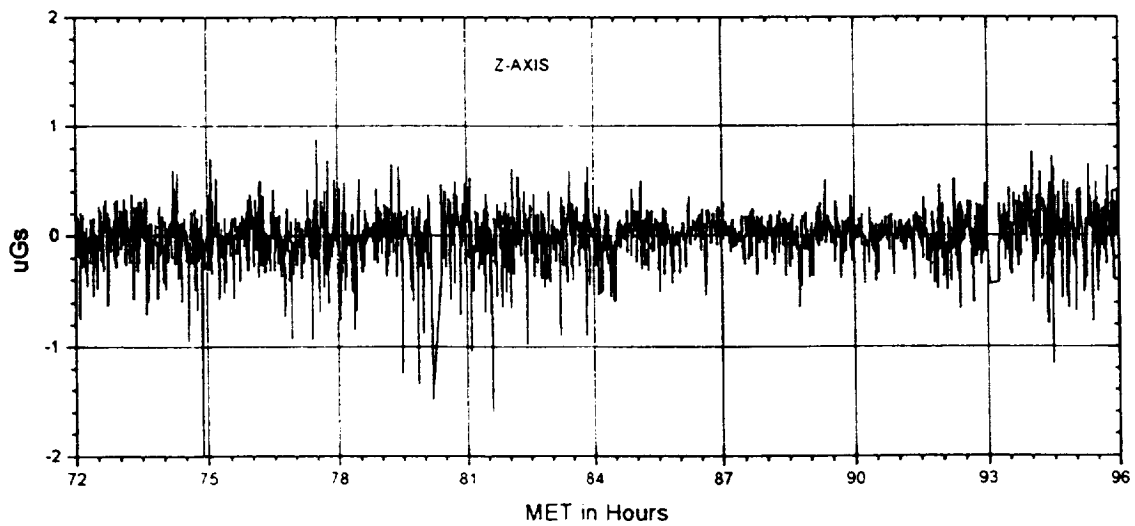
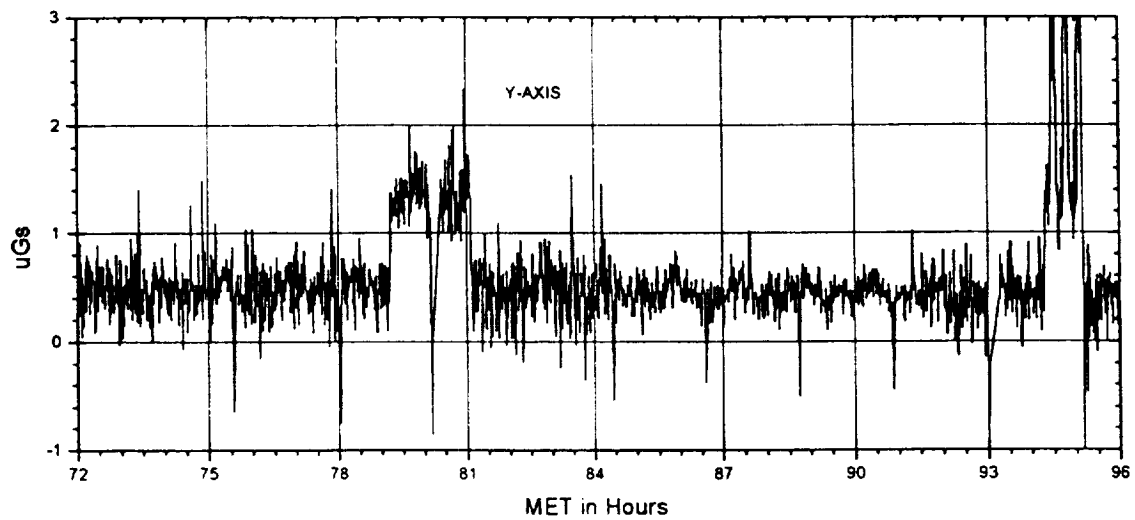
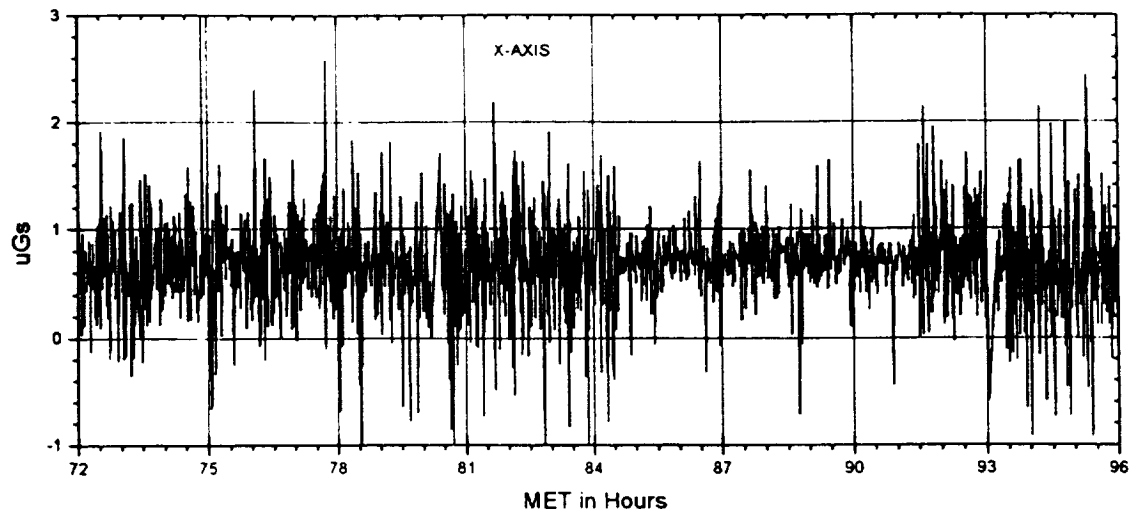


Figure 4. Measured acceleration for MET 72-96 hours.

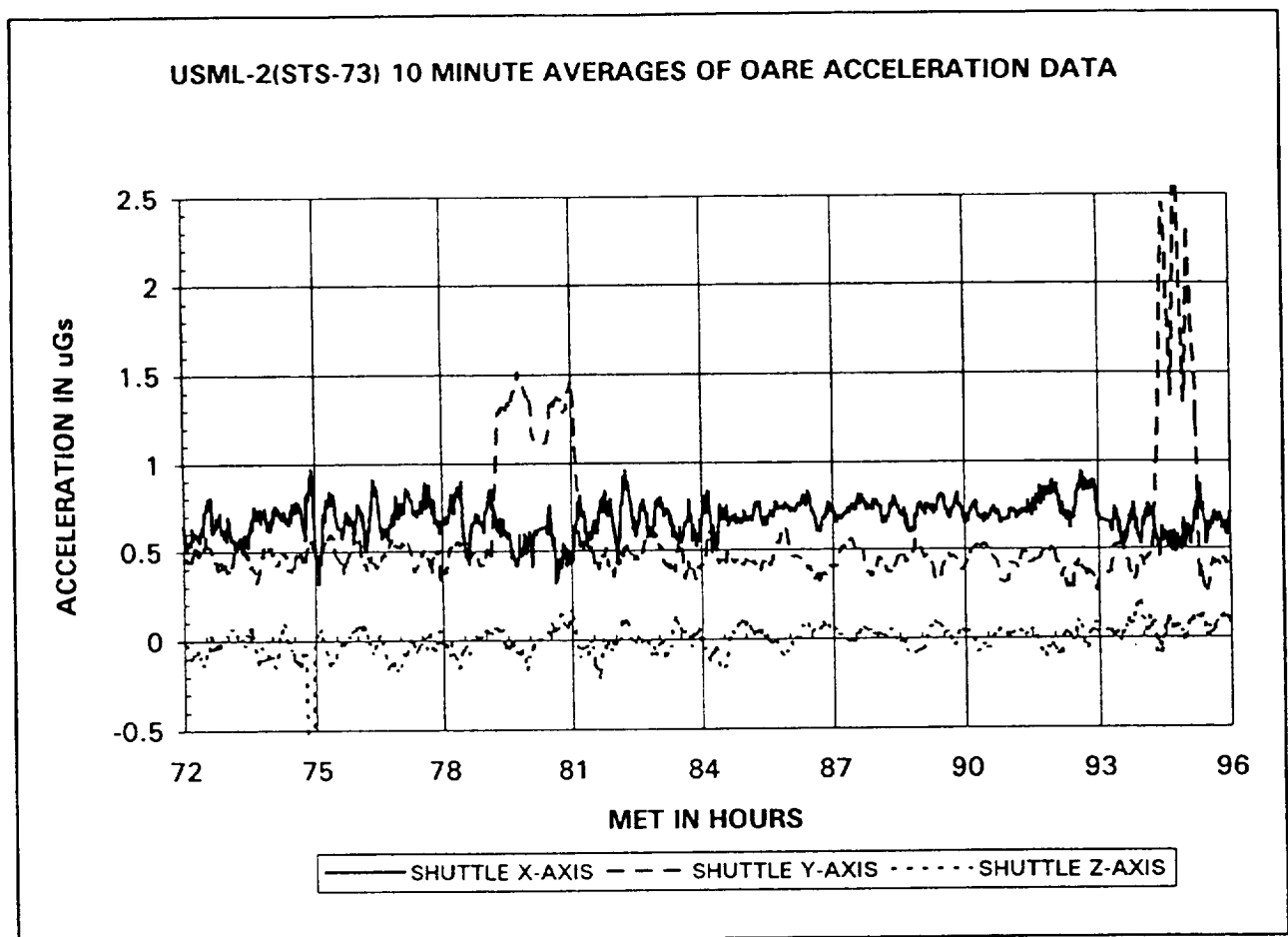


Figure 5. OARE acceleration data averaged over 10 minutes in order to better show orbital effects.

2.5 STS-73 Anomalous Performance

On STS-73 there was one anomaly which was in general minor in nature. This had been seen on previous missions and was not considered significant enough to fix at that time. The following is a discussion of this anomaly.

OARE Z Axis Scale Factor Anomaly

OARE's performance on STS-73 was similar to that on STS-65 and STS-62. The Z-axis C-range scale factor calibration was still affected by jitter to a small degree. In addition, the OARE instrument in the C-range continued to show the characteristics of an "electronic bias shift" that was first noted in STS-58 [4]. The electronic bias shift manifested itself with small changes in the pre- and post-rate levels during the scale factor calibration on the Z-axis in the C-range. This electronic bias shift was not apparent in the bias calibrations and appears to be an artifact that occurs only during the scale factor calibration period and, hence, does not affect the Z-axis data collection.

3.0 OARE ACCURACY ANALYSIS

The OARE instrument provides high resolution measurements of sensor input axes accelerations, 3.05 nano-Gs in the OARE X-axis and 4.6 nano-Gs for the Y and Z axes. The accuracy of these measurements is primarily determined by the degree to which the instrument can be calibrated over the time period of the measurements. Major sources of potential errors are the accuracies obtainable from the bias and scale factor calibrations.

3.1 Bias Errors

On STS-73, the bias was measured 170 times. From these measurements, the true bias was estimated by the fitting procedure discussed in Appendix A. Potential errors in these bias estimates arise from the statistical nature of the bias measurements as well as from potential systematic errors which have not been identified. Based upon the analysis contained in Appendix A, we estimate that the bias errors are approximately 30 to 50 nano-Gs. These are consistent with the earlier analysis contained in the STS-65 Final Report [5].

3.2 Scale Factor Errors

In the microgravity environment of the Orbiter, the quasi-steady acceleration measurements are typically on the order of 1 micro-g or less. Under these conditions, the bias errors are larger than the scale factor errors.

Measurements of the scale factors made during flight and those on the ground are now consistent to within 1 to 2 percent. We estimate the scale factor errors to be about 1 to 2 percent of the measured acceleration. These can be reduced with further study. At a 1 micro-g level, this corresponds to a 10 to 20 nano-G error. These should be added in quadrature with the bias errors. So overall, this gives estimated errors for the on-orbit acceleration measurements of about 30 to 60 nano-Gs.

3.3 Quasi-Steady Acceleration Measurements

As indicated, the primary OARE data recorded on the flight computer is processed through an adaptive trimmean filter. This trimmean filter provides a near optimum estimate of the mean of the quasi-steady acceleration population of measurements over the 50 second sampling period. This estimate is particularly beneficial in the calculation of the bias estimate and the estimate of orbital drag and gravity gradient effects. However, it tends to reject the effects of crew activity, thruster firings, and other exogenous events. Because many experimenters are interested in the true average of the acceleration measurements over the 50 second sample period, we are now considering incorporating the true average as well as the trimmean average for the sampling periods into the data recorded on the flight computer. In any case, the true average can be recovered from the telemetry data on STS-73 for those periods where it exists.

4.0 REFERENCES

- 1) R.V. Hogg, "Adaptive Robust Procedures: A Partial Review and Some Suggestions for Future Applications and Theory," Journal of American Statistical Association, Vol. 69, Number 348, December 1974, pp 909-927.
- 2) T. DeWet, J.W.J. VanWyk, "Efficiency and Robustness of Hogg's Adaptive Trim Means," Commun. Statist.-Theor. Meth., A8(2), pp 117-128, 1979.
- 3) "STS 62 Final Report," OARE Technical Report #145: Canopus Systems, Inc., July 1994.

4) "OARE Flight Maneuvers and Calibration Measurements on STS-58," NASA TM-109093, R.C. Blanchard, J.Y. Nicholson, J.R. Ritter, K.T. Larman, April 1994.

5)"STS-65 Final Report," OARE Technical Report #146, Canopus Systems, Inc., November 1994.

APPENDIX A

OARE DATA CALIBRATION

This Appendix reviews the methods used to calculate the Orbiter body triaxial acceleration based on the OARE instrument measurements which were recorded on the EEPROM and later downloaded and processed by Canopus Systems. The method of estimating the sensor bias has evolved over the past several missions; STS-73 is the first mission where a full weighted least squares methodology has been implemented in estimating the instrument bias. The Appendix begins with the instrument model (A1), discusses the robust estimator known as the trimmean algorithm which is used to estimate the quasi-steady acceleration (A2), discusses the bias measurements and their estimated measurement errors (A3), and finally presents the weighted least squares estimate of the bias of the instrument (A4). A short discussion of Scale Factor calibration is also given (A5).

A1 INSTRUMENT MODEL

The OARE instrument acceleration for each axis and range is calculated from an equation of the form

$$A_A = -SF_C * SF_N * (CTS - 32768 - BIAS) \quad (\text{eq. 1}), \text{ where}$$

A_A is the calibrated actual acceleration in uGs,
 SF_C is the Scale Factor Calibration term,
 SF_N is the Nominal Scale Factor in uGs per count,
CTS is the counts out of the instrument A/D converter, and
BIAS is the estimated Bias in counts as a function of time and temperature,
where each of the terms is dependent upon the particular axis and range.

In the above equation, the number 32768 appears because the 16-bit A/D converter is single-ended; this value is the offset required to obtain a zero measured acceleration for a zero input acceleration.

An Actual Scale Factor SF_A term is defined by

$$SF_A = SF_C * SF_N \quad (\text{eq. 2}).$$

Values of the nominal scale factor, SF_N , are given in Table 1 of the main report for each OARE axis and range. Values of SF_C for the OARE X, Y, and Z axes are approximately 1.02, 1.11, and 1.10, respectively, but are determined through calibration on each STS mission for each axis and range.

The output of the A/D converter provides a digital acceleration data sample which is effectively processed at a rate of 10 times per second. Data are stored on the EEPROM at a rate of once every 25 seconds, and these data represent the filtered estimate of the quasi-steady acceleration value over a 50-second period. The data presented in this report are based upon the EEPROM data (CTS above) which contain "trimmean averages" over 50-second

periods (trimmean average of 500 acceleration measurements) reported at 25-second intervals.

A2 TRIMMEAN ESTIMATE OF ACCELERATION

The OARE instrument is designed to measure the quasi-steady acceleration from below 10 nano-Gs up to 25 milli-Gs and over the quasi-steady bandwidth from 10^{-5} to 10^{-1} Hz. The quasi-steady acceleration components of primary interest are those due to gravity gradient, on-orbit drag, inertial rotations, and perhaps long period venting or gas leaks. However, the instrument is subjected to higher amplitude and higher frequency accelerations (such as structural vibration, station keeping thruster firings, and crew effects) in addition to the quasi-steady accelerations. These higher level accelerations are not well characterized nor statistically invariant over the OARE measurement periods.

In order to obtain a more optimum estimate of the quasi-steady acceleration under these conditions, a robust adaptive estimator has been implemented. For a discussion of robust estimators, see Reference 1. The particular estimator implemented in OARE is known as the Hogg Adaptive Trimmean estimator and is described in more detail in Reference 2.

In essence, the trimmean adaptive filter removes a percentage of the distribution from each tail and then calculates the mean of the remaining distribution. It first measures the departure of the sample distribution from a normal (Gaussian) distribution as measured by a parameter called Q, then adaptively chooses the amount of the trim to be used on the distribution, and finally calculates the mean of the remaining distribution after the trim.

As implemented, Q is defined by the following equation:

$$Q = [U(20\%) - L(20\%)]/[U(50\%) - L(50\%)] \quad (\text{eq. 3}), \quad \text{where}$$

U(X%) is the average of the upper X% of the ordered sample, and
L(X%) is the average of the lower X% of the ordered sample.

In the OARE case, the ordered sample is typically a sample of 500 acceleration measurements of the A/D output over a 50-second measurement period.

Q is a measure of the outlier content in the sample. For a Gaussian distribution, Q is 1.75; for samples which have larger tails, $Q > 1.75$. The value of Q is used to estimate the extent that the quasi-steady acceleration measurements may be contaminated by thruster firings, crew activities, etc.

In order to improve the estimate of the quasi-steady acceleration, a trimmean is used to estimate the mean of the quasi-steady population. A trim parameter alpha is determined by the following algorithm:

$$\alpha(Q) = \begin{array}{ll} 0.05 & \text{for } Q \leq 1.75 \\ 0.5 + 0.35 * (Q - 1.75) / (2 - 1.75) & \text{for } 1.75 < Q < 2.0 \quad (\text{eq. 4}) \\ 0.4 & \text{for } Q \geq 2.0, \end{array}$$

where alpha is the fraction of the distribution which is trimmed off each tail of the ordered distribution before the mean of the remainder of the distribution is calculated.

Then, for an underlying distribution of n points or measurements with a value of alpha, the trimmean is given by

$$\text{trimmean} = [X_{(k+1)} + X_{(k+2)} + \dots + X_{(n-k)}] / (n-2*k), \quad (\text{eq. 5}),$$

where $k = \alpha * n$ (eq. 6) and

$X_{(i)}, X_{(i+1)}, \dots, X_{(n)}$, is the ordered set of n points making up the sample distribution.

In summary, OARE measures the quasi-steady level of acceleration for each axis every 25 seconds by taking the trimmean of the previous 50 seconds of A/D counts (500 samples in total) according to equations 3 through 6, and then substituting this trimmean for CTS in equation 1.

Data recorded on the EEPROM and available to support the acceleration calculations include the trimmean of the 50-second distribution every 25 seconds, the Q of this sample distribution, the Average Deviation from the trimmean of the distribution used to calculate the trimmean, the instrument temperature, the Mission Elapsed Time (MET), and numerous housekeeping parameters.

The widths of the 500 sample distributions (as measured by the standard deviations) are almost entirely due to the environment aboard the shuttle and not due to sensor noise. This is illustrated in Figure A-1, where the trimmean counts for the OARE X-Axis is plotted for MET from 54 to 72 hours on STS-62. On STS-62, the whole crew had common sleep periods as can be noted by the small variation in the data obtained during a sleep period from about 59 to 65 hours. During this period, the instrument output is extremely quiet as opposed to periods when there is crew activity. On STS-65 and STS-73, the crew was active 24 hours per day and consequently caused noisier data from a quasi-steady point-of-view.

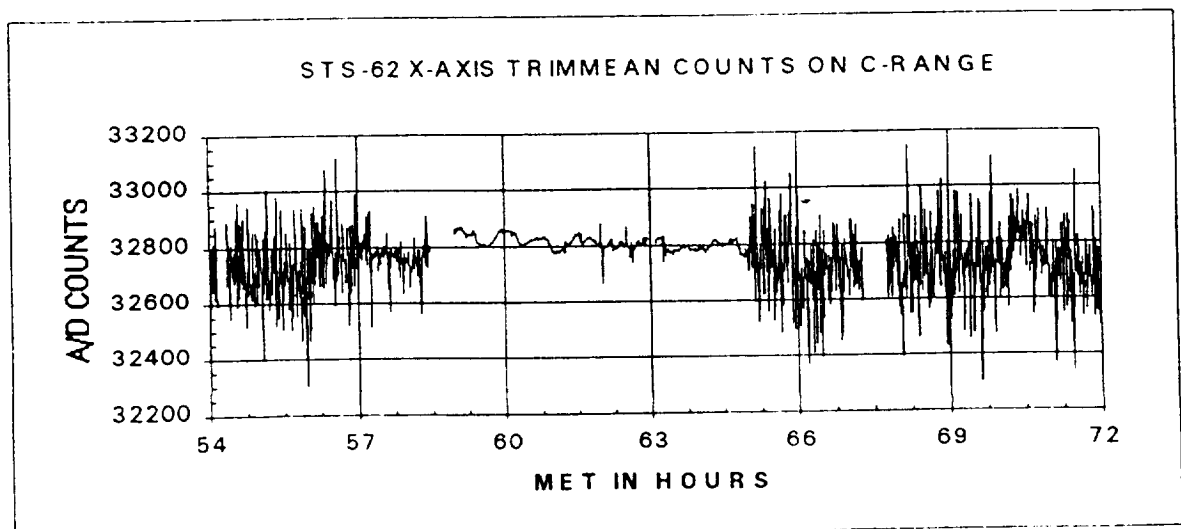


Figure A-1. STS-62 X-Axis Trimmean Counts on C-Range showing a sleep period.

A3 BIAS MEASUREMENTS AND ESTIMATED MEASUREMENT ERRORS

As can be seen in Equation 1, the calculated acceleration depends upon the instrument bias. This is a critical parameter in accelerometers that are designed to measure quasi-steady accelerations below 1 milli-G. For on-orbit conditions, the typical quasi-steady acceleration is less than 1 micro-G. Thus, the bias estimate is absolutely critical to accurate acceleration measurements in this regime.

The OARE accelerometer uses an electrostatically suspended proofmass in order to minimize the effects of temperature and mechanical suspension hysteresis on the bias. In addition, OARE incorporates a two-axis gimbal calibration table by which the OARE instrument can be calibrated on-orbit for bias and scale factor in each of its three axes.

A3.1 Bias Measurements

The bias measurement for a single axis consists of the following sequence: 1) measuring the acceleration output in trimmean counts for 50 seconds in the normal table position for a given axis (called $BIAS_N$), 2) rotating the input axis 180° , and then 3) measuring the acceleration output in trimmean counts (called $BIAS_I$, for inverted position). Assuming that the actual input acceleration remains constant during this period (about 125 seconds), as might be expected for quasi-steady accelerations, then the bias can be calculated by

$$BIAS_M = (BIAS_N + BIAS_I)/2 - 32768 \quad (\text{eq. 7}), \text{ where}$$

$BIAS_M$ is the measured bias for a particular axis,
 $BIAS_N$ is the bias measurement in the normal position, and
 $BIAS_I$ is the bias measurement in the inverted position.

During a single mission, the bias is measured for each axis many times for the C-range. These bias measurements then provide the basis for estimating the bias time history throughout the mission. The bias estimates are ultimately determined by fitting a functional form through these bias measurements, as will be discussed in A.3.5.

A3.2 Sources of Noise Associated with the Bias Measurement

The sources of noise which contribute to measurement errors on the bias measurements are largely associated with crew activity, as indicated in Figure A-1. The bias measurement accuracy depends upon the input acceleration remaining constant during the time that the bias measurements are being made. The time difference between the two positions used in the bias measurements is about 75 seconds--corresponding to every 3rd measurement point in Figure A-1. Clearly, the input acceleration is varying except during the times when the whole crew is asleep. During most missions, one segment of the crew is active at all times--as was the case on STS-73. Under these conditions, the bias measurements contain significant measurement errors which cannot be eliminated. However, the expected mean of the errors should be zero since both bias measurement positions are equally likely to be affected.

An example of bias measurement data for the two 50-second periods used to calculate a bias from the telemetry data on STS-73 is shown in Figure A-2. This bias measurement sequence is at MET of 48.0 hours and shows the two X-Axis C-Range bias measurement positions. It illustrates some typical input accelerations (noise) observed when making the bias measurements. We have indicated on the plots the respective trimmean, Q, Average Deviation, and Standard Deviation values associated with each bias measurement period.

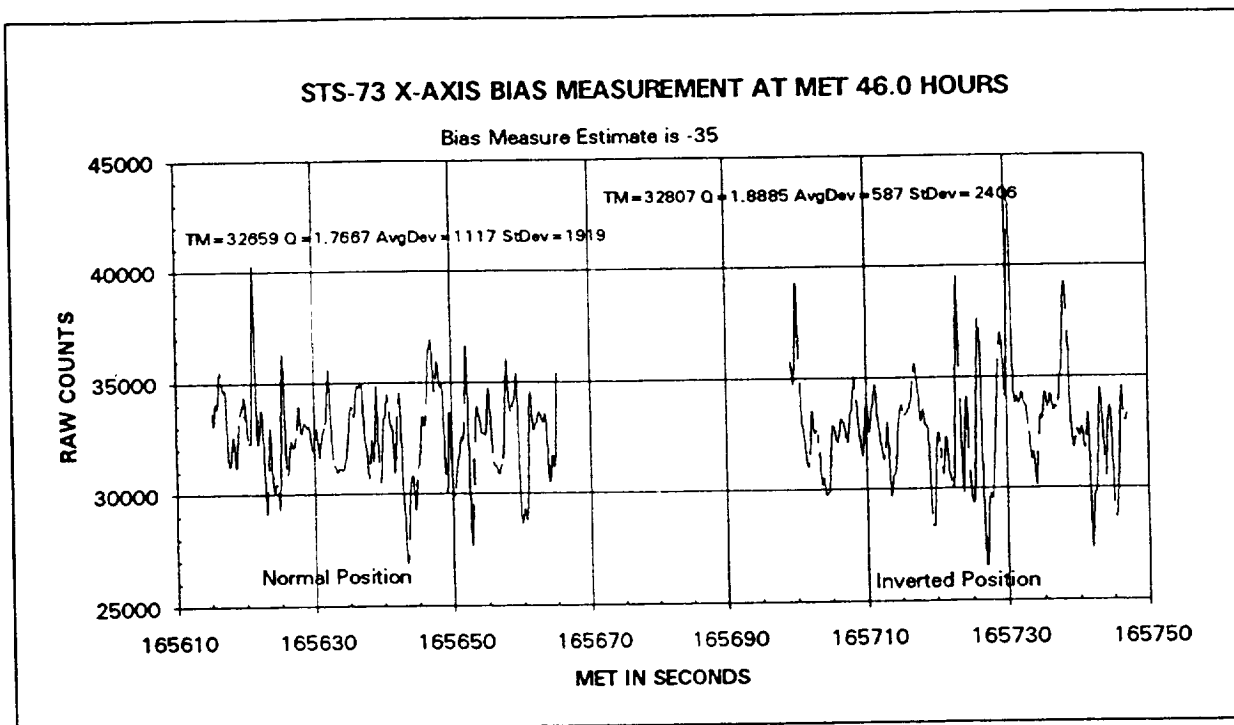


Figure A-2. Representative Bias Measurement Traces on STS-73.

An important consideration is the estimate value of the errors associated with the measurement of the quasi-steady acceleration during the bias measurements as a result of the "noise" contamination of the quasi-steady population distribution due to crew activity and associated effects. These errors are a direct measure of the bias measurement accuracy.

A3.3 Estimate of the "Error" in the Bias Measurement

In the calculation of the bias, the quantity $(BIAS_N + BIAS_I)$ appears in equation 7 where $BIAS_N$ and $BIAS_I$ are the calculated trimmean values of the A/D over two 50-second periods about 75 seconds apart. The errors associated with the bias measurement are directly associated with the variation in the input acceleration during these two measurement periods.

On STS-65, Canopus Systems received extended periods of downloaded tape recorder data which contained the direct measurement of acceleration from the A/D at the ten sample per second rate. We have used this data to statistically examine the trimmean measurement of

acceleration over the 50-second measurement period typical of bias measurements and its variation over the 125 seconds required to make bias measurements.

We have examined the statistical properties of the set $\{Z_i\} = \{Y_i - Y_{i+75}\}$, where Y_i is the trimmean acceleration measurement at time i (output of the A/D in counts over a 50-second measurement period, i.e., 500 count values from the A/D) and Y_{i+75} is the trimmean acceleration measurement at time $i + 75$ seconds. In a quiet environment where there was only the quasi-steady accelerations due to gravity gradient and orbital drag, one would expect this difference to be nearly zero since neither of these sources are expected to change on a time scale of 75 seconds. Consequently, the amount that this difference differs from zero is an indication of the amount of contamination of the measurement of the quasi-steady acceleration as a result of crew activity, or looked at another way, it is a measure of the measurement error on the quasi-steady acceleration measurement.

We examined possible ways of estimating when this difference quantity might not be zero. In classical statistics, the error estimate on the difference of two quantities is equal to the root sum of squares of the estimate of the error on the two quantities being differenced. As a result, a good means of estimating the error on this difference might be root sum of squares of the standard deviations of the populations of the 500 measurements used in the calculation of each Y . This is motivated by the fact that the classical estimated error on the mean of a population is the standard deviation of the sample distribution divided by the square-root of the number of points in the sample. (We have ignored the square-root of 500 factor in the following regression since it is essentially constant for all of the samples.)

Figure A-3 shows a scatter plot of the 75-second trimmean differences, $\{Z_i\}$, versus the square-root of the sum of the standard deviations of $\{Y_i\}$ and $\{Y_{i+75}\}$ about the trimmeans (RSSD) for the X-Axis acceleration measurements on the C-range over a period of 37 hours on STS-65. Here, RSSD means Root Sum of Squares of Standard Deviations. As expected these trimmean differences have zero mean and the probability that they differ from zero increases as RSSD increases.

The 5339 points were then grouped in 13 bins of 400 each based upon the value of the RSSD; the remaining 139 points were discarded as extreme outliers. The $\text{RMS}\{Z_i\}_j$ for each bin j was then calculated and plotted against the $\text{Average}\{\text{RSSD}_i\}_j$. Figure A-4 shows a regression of these two quantities for the OARE X-Axis. As indicated, an R-squared value of 0.98 was obtained, indicating that RSSD is indeed a good indicator of the expected difference from zero of two trimmean measurements taken 75 second apart.

Similar analyses were performed for the OARE Y and Z axes. The results of regressing the RMS of the trimmean differences against the Average of RSSD are shown in Figures A-5 and A-6. In each case, good R-squared values were obtained where the smallest 80% of the RSSD values were used. For larger RSSD values, the errors on the trimmean were less than would be estimated from the regression analysis projection. This is a result of the improved performance of the trimmean estimator over the classical average estimator when there are large tails in the distribution.

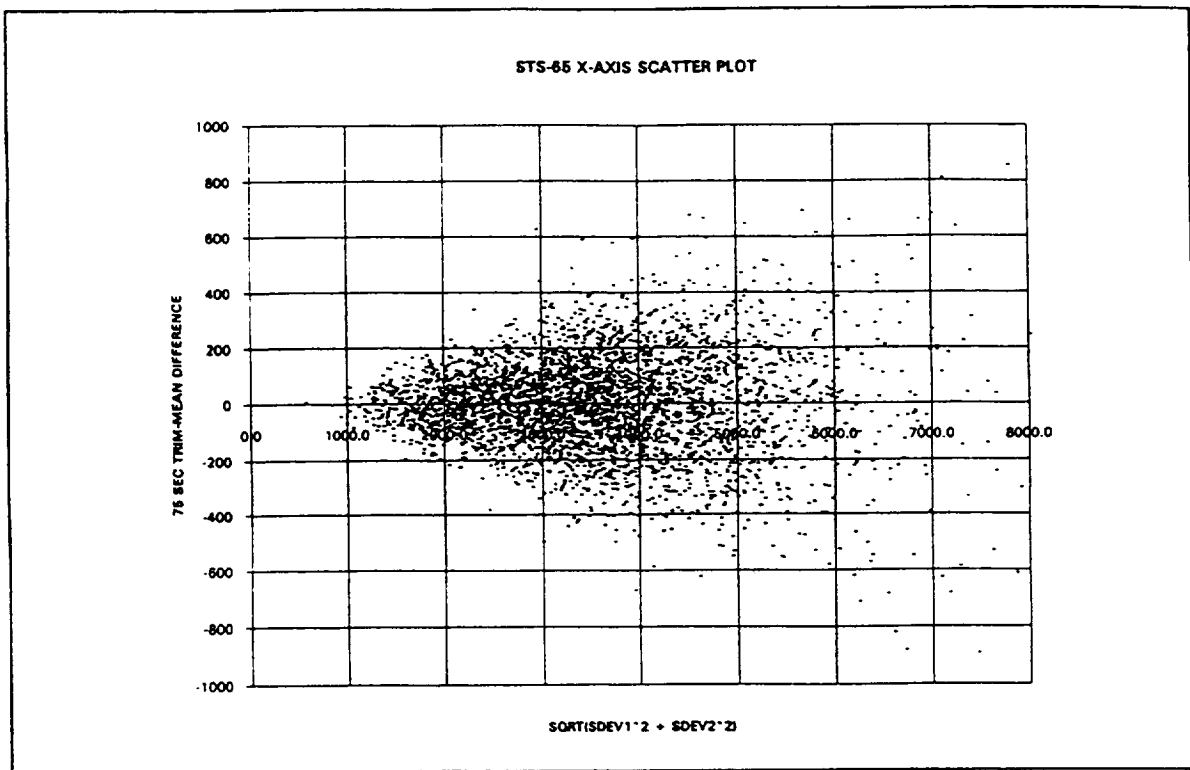


Figure A-3. Scatter plot of $\{Z_i\}$ (75 second trim mean differences) versus RSSd for the X-Axis on STS-65.

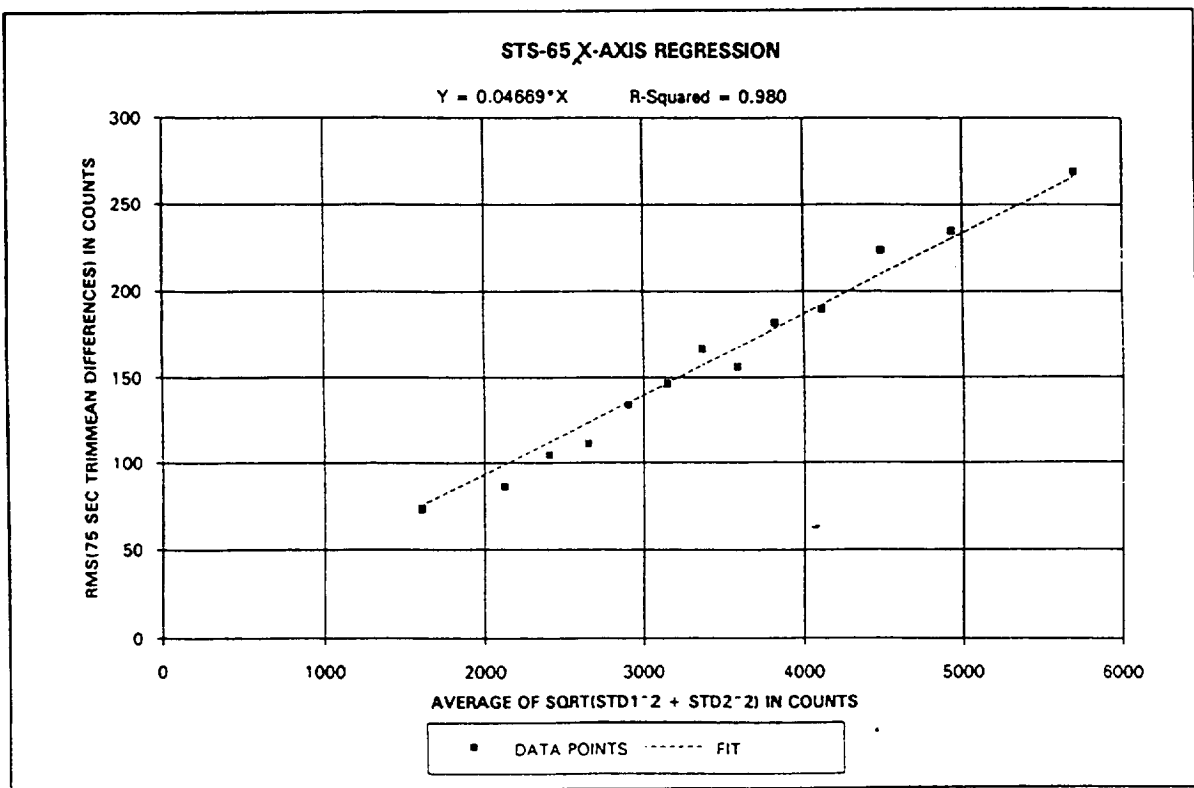


Figure A-4, Regression of RMS of $\{Z_i\}$ versus Average of RSSd for X-Axis.

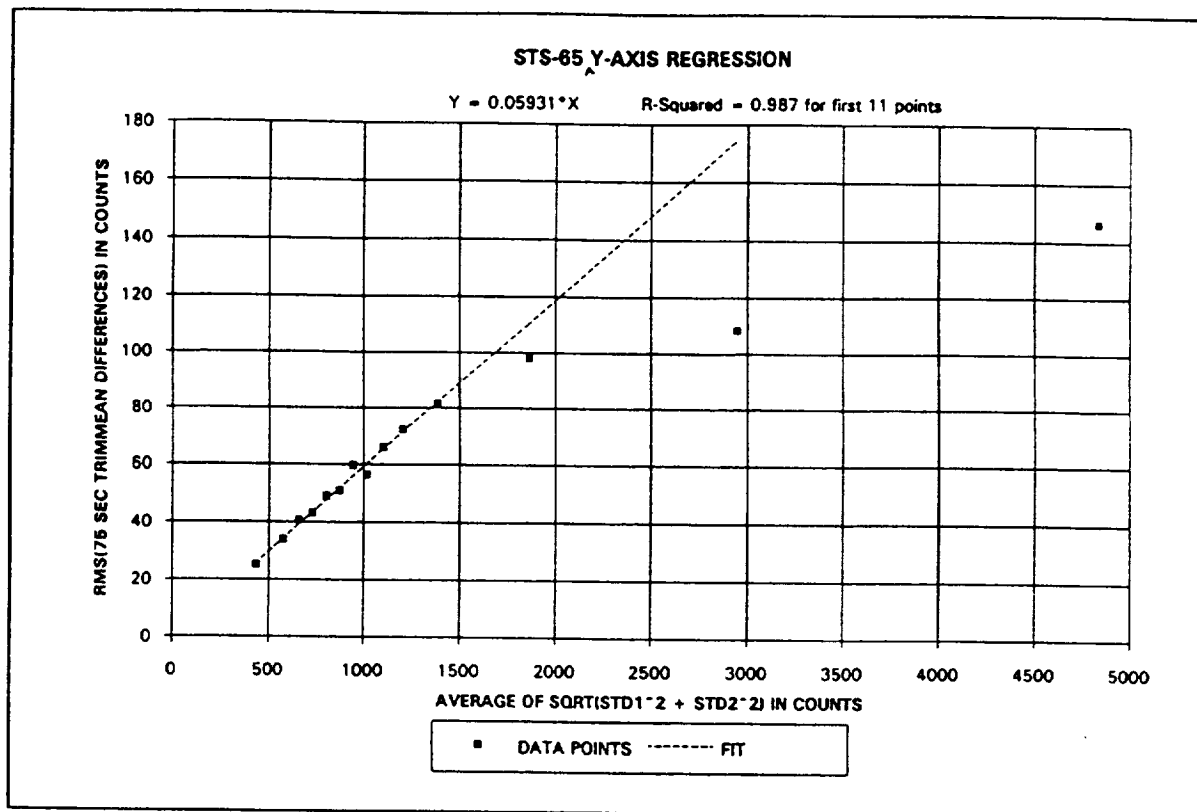


Figure A-5, Regression of RMS of $\{Z_i\}$ versus Average of RSSd for OARE Y-axis.

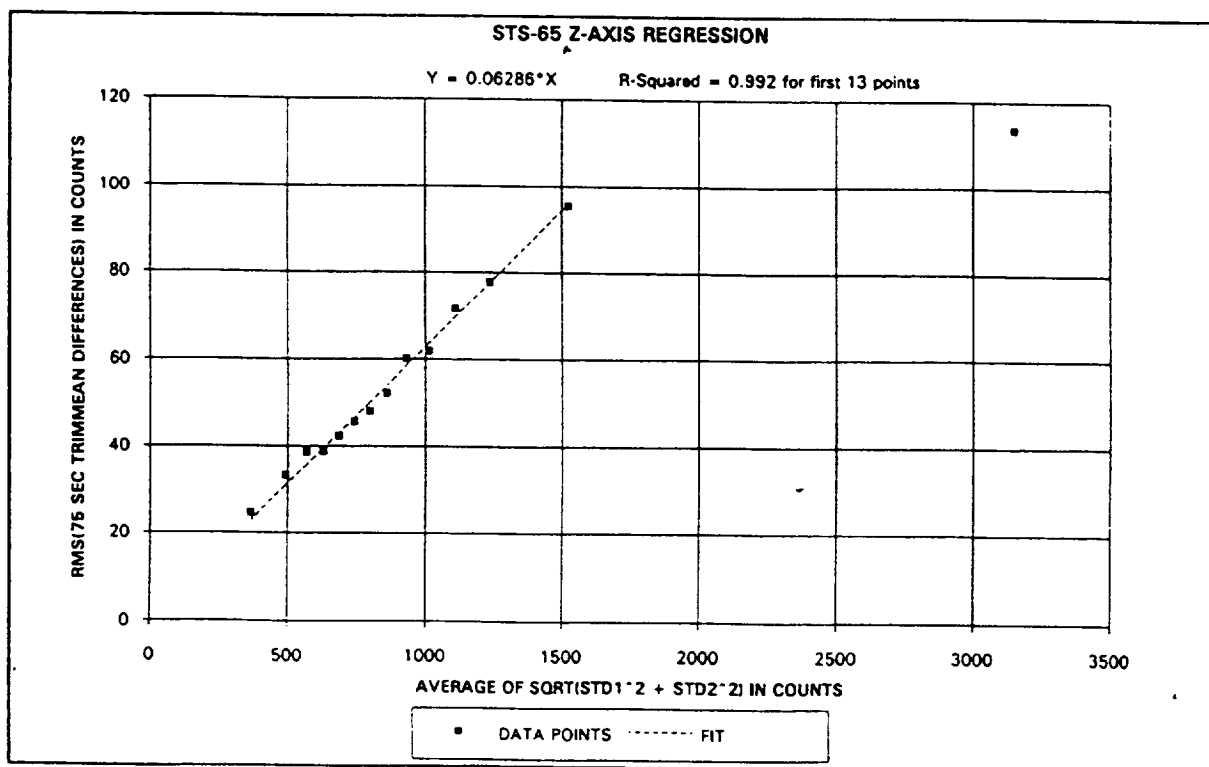


Figure A-6, Regression of RMS of $\{Z_i\}$ versus Average of RSSd for OARE Z-axis.

A number of other metrics were tested in trying to develop a relationship between the RMS of the trimmean differences and the other metrics associated with the two separate distributions. Metrics tested were based upon Q, alpha, the trimmed AvgDev, a normalized AvgDev, a normalized Winsorized standard deviation, the width of the distribution as measured U(50%)-L(50%), the third moment, and difference between the average and the trimmean. None of these other metrics was found to give superior performance to the one based on the classical standard deviation presented above.

Of course, the "measurement errors" associated with the quantity $BIAS_N + BIAS_I$ have the same properties as those associated with $Y_i - Y_{i+75}$, where "measurement error" denotes the difference between the value measured and that which would have been measured if the distributions had not been contaminated by non-quasi-steady accelerations due to crew and other exogenous activities. Since the bias is calculated by

$$BIAS_M = (BIAS_N + BIAS_I)/2 - 32768 \text{ (eq.7),}$$

the measurement errors associated with the bias measurement should be 1/2 of the RMSs associated with the trimmean differences discussed above.

A3.4 Estimate of the Standard Deviation from EEPROM Available Data

We have shown above that the standard deviation of the set of 500 measurements provides a reasonable basis for estimating the error associated with using the trimmean as an estimate of the quasi-steady acceleration, and that the RSSD of the standard deviations of the measurements made at the two bias positions provides an estimate of the measurement error associated with a given bias measurement.

However, in the development of the OARE flight system, processing power and on-board storage were very limited. As a result, the on-board system never calculates the standard deviation associated with a particular set of 500 samples which are processed by the trimmean filter. Only the value of Q, alpha, Average Deviation of the trimmed data set, and the Trimmean are calculated for each data set. Q, Average Deviation, and the Trimmean are stored on the EEPROM for every set of 500 samples independent of whether they correspond to a normal acceleration measurement or a bias measurement. Consequently, using only the EEPROM data, the standard deviations must be estimated from these parameters.

Based upon the telemetry data from STS-65, we have developed a relationship between Q, alpha, and the AvgDev. The relationship is derived by estimating the expected standard deviation if the original sample has been a perfect normal (Gaussian) distribution, and then estimating the effect of the non-Gaussian distortion based upon the measured Q value.

The theoretical standard deviation for a perfectly normal distribution StDevT can be shown to be

$$StDevT = (\text{Sqrt}(2 \cdot \pi) \cdot \text{AvgDev} \cdot (0.5 - \alpha)) / (1 - \exp[-\phi^{-1}(\alpha)^2/2]) \text{ (eq. 8),}$$

where $\phi^{-1}(\alpha)$ is the inverse of the standard normal cumulative distribution for the value of α and AvgDev is the average deviation of the distribution after each tail has been trimmed by the amount α .

As might be expected, in the OARE data this theoretical standard deviation is less than that actually measured since the tails were often larger than for a normal distribution, as indicated by a Q value greater than 1.75.

Figure A-7 shows a plot of the difference between this theoretical value (StDevT) minus the measured value (StDevM) divided by the measured value as a function of Q for the X-Axis from STS-65. As can be seen, the theoretical standard deviation is too small when Q is greater than 1.75, but the difference is zero when the Q value corresponds to a Gaussian distribution.

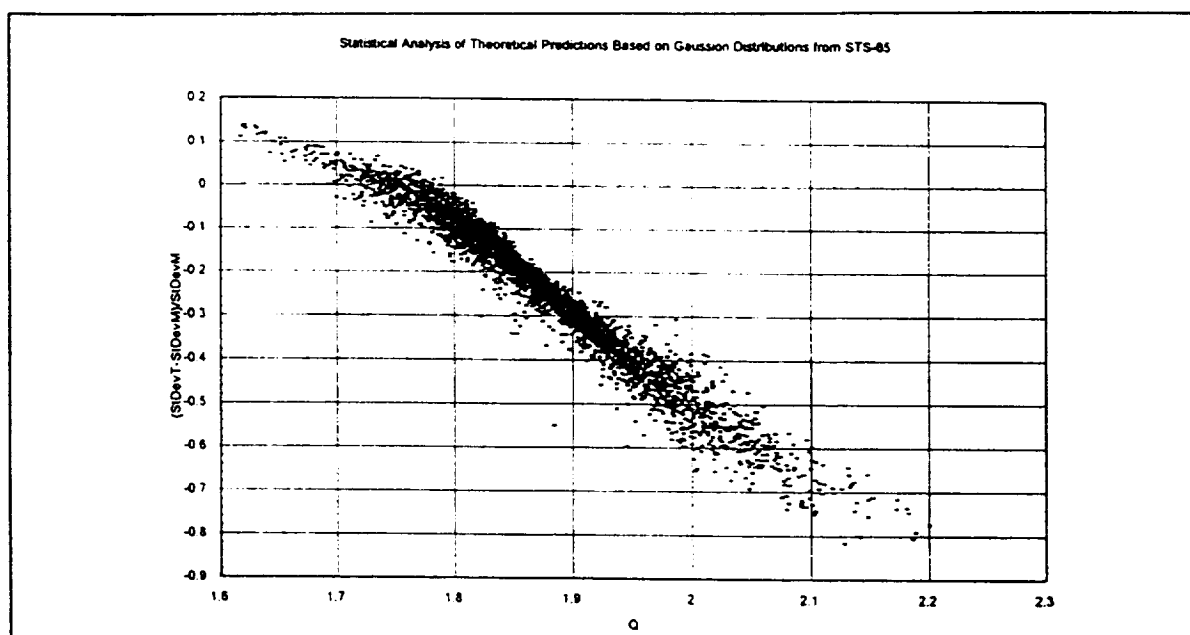


Figure A-7. Relationship Between Normal Gaussian Standard Deviation Prediction, Measured Standard Deviation, and Q.

The predicted standard deviation StDevP can then be determined from such a plot. The predicted standard deviation is related to the theoretical standard deviation by the following equation:

$$\text{StDevP} = \text{StDevT} / (1 - m \cdot (Q - 1.75)) \quad (\text{eq. 9}),$$

where m is a fitted coefficient for each axis, [$m = 1.98, 1.86$, and 1.98 for OARE X, Y, and Z axes, respectively].

Figures A-8, A-9, and A-10 show the plot of Predicted Standard Deviations and Measured Standard Deviations for 4000 data sets for STS-65 for the OARE X, Y, and Z axes, respectively. In general, the predicted values agree quite well with the measured values and

the relationship developed between StDevP and AvgDev and Q will serve as a basis of estimating the measurement error on the bias measurements on STS-73.

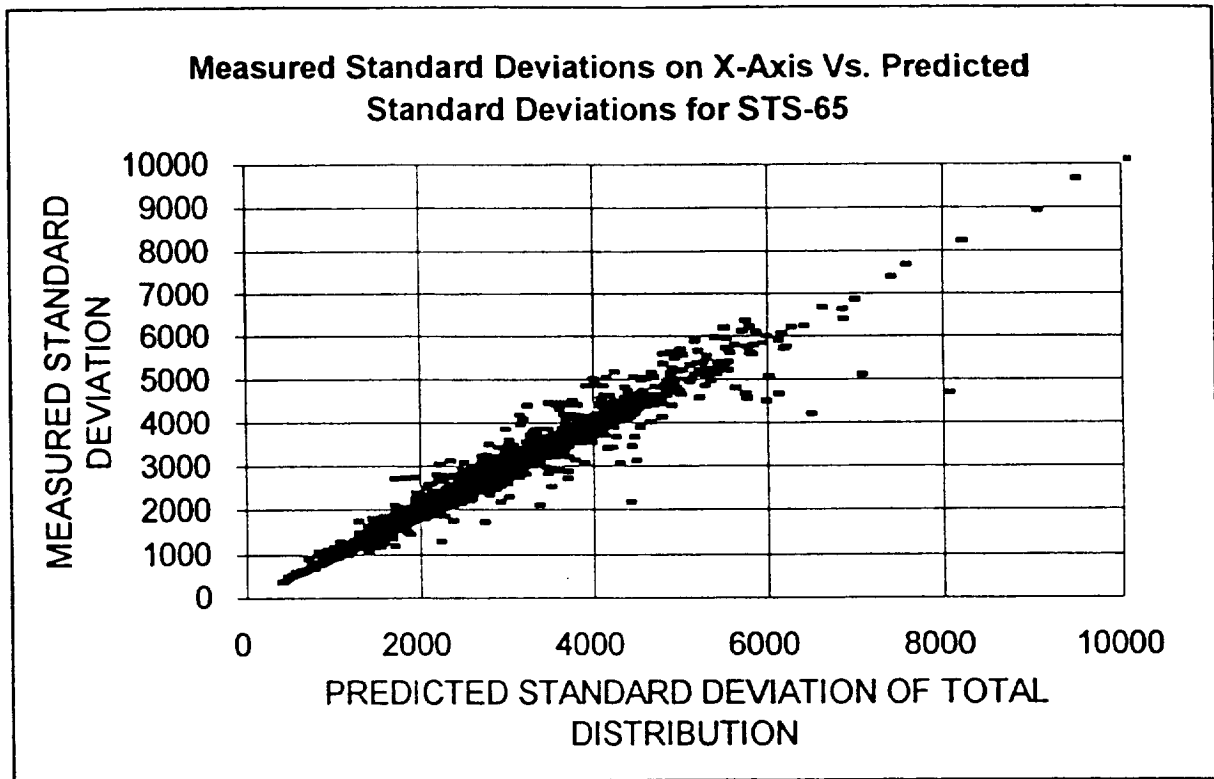


Figure A-8. Measured Standard Deviations vs. Predicted Standard Deviations for X-Axis.

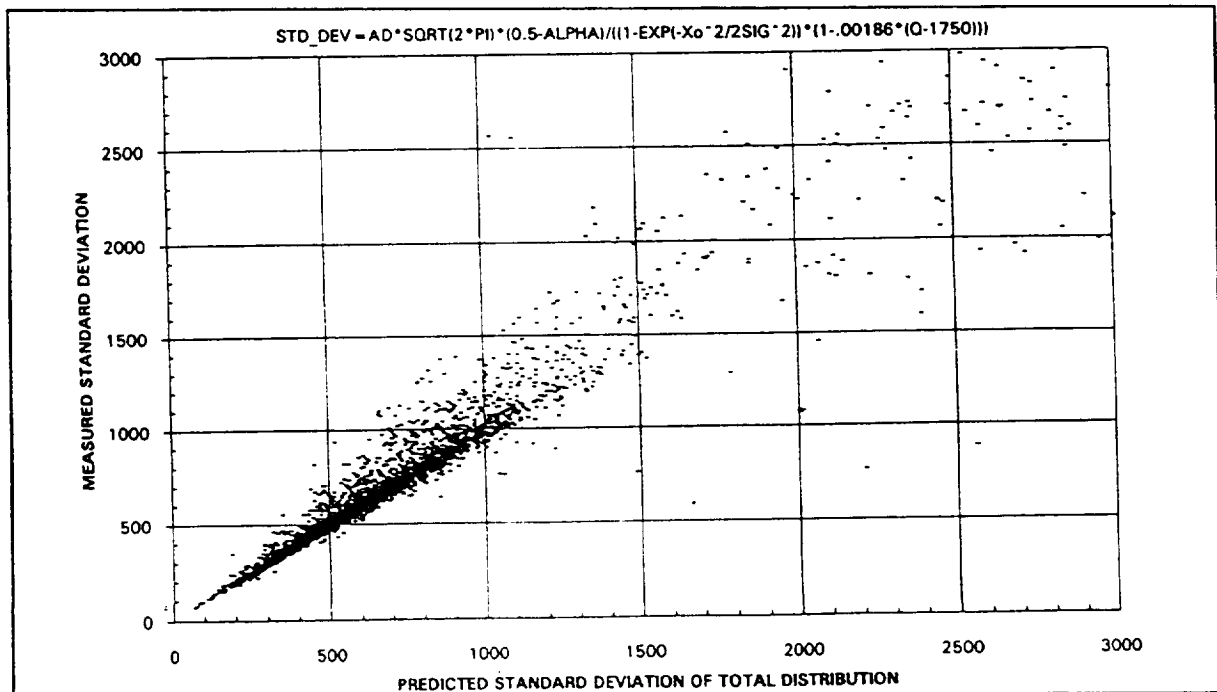


Figure A-9. Measured Standard Deviations vs. Predicted Standard Deviations for Y-Axis.

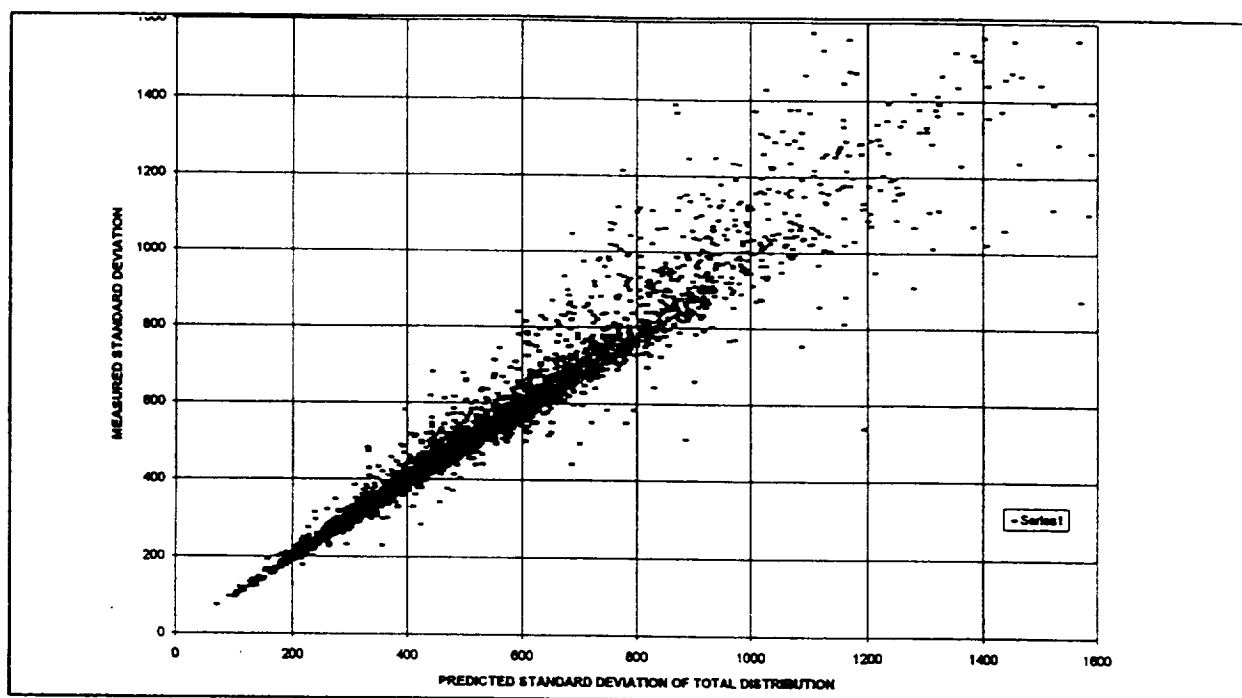


Figure A-10. Measured Standard Deviations vs. Predicted Standard Deviations for Z-Axis.

On STS-73, we had a subset of the bias measurements available from the telemetry data. We calculated the RSSd from measured standard deviations and compared them with the predicted RSSd using the EEPROM data alone for the biases where both were available. A scatter plot of the bias estimated errors on STS-73 are shown in figures A-11, A-12, and A-13 for the OARE X, Y, and Z axes, respectively.

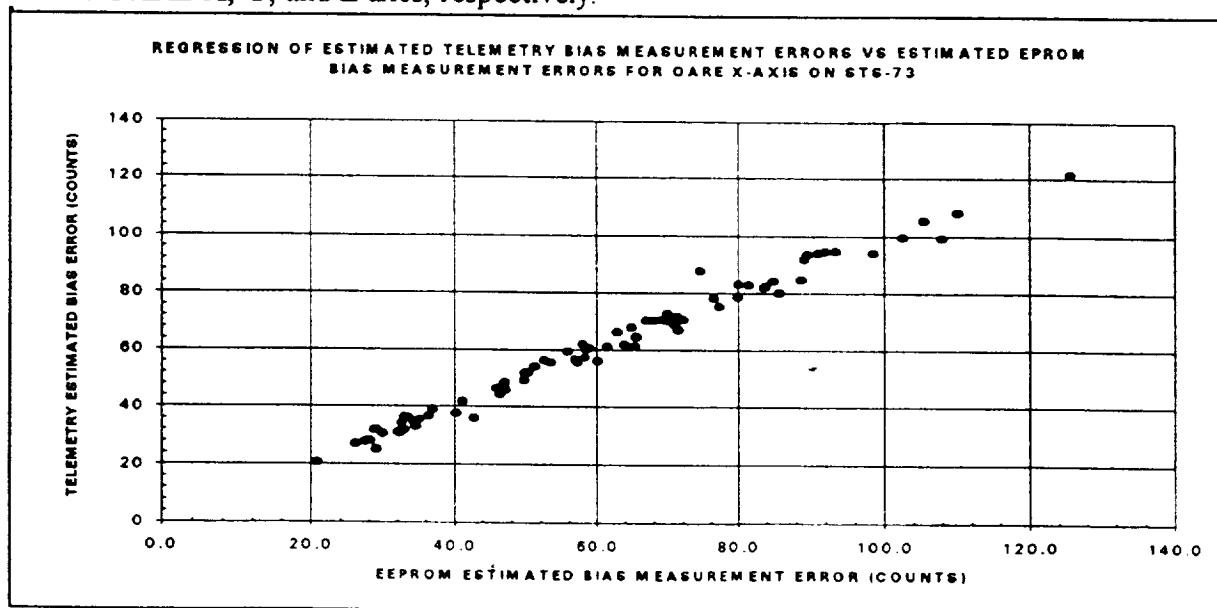


Figure A-11. Comparison of Estimated Bias Errors from Telemetry and EEPROM for same Bias Calibrations.

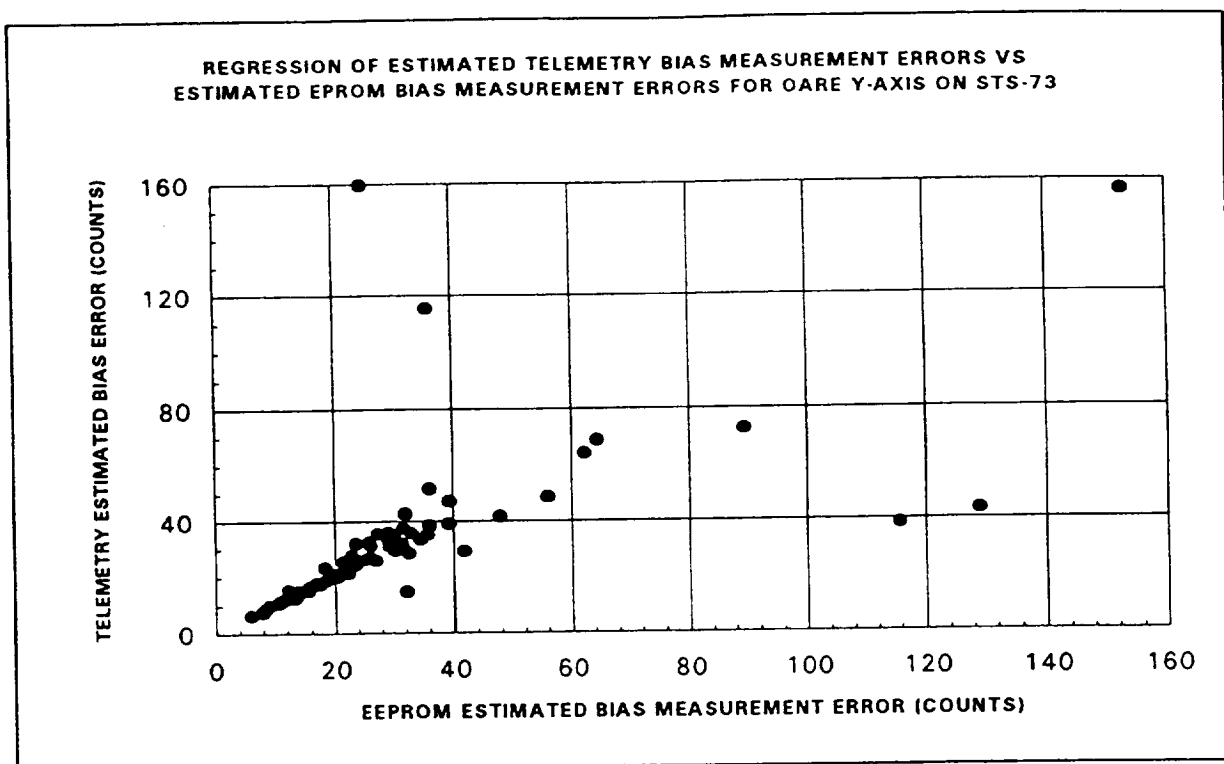


Figure A-12. Comparison of Estimated Bias Errors from Telemetry and EEPROM for same Bias Calibrations for Y-Axis.

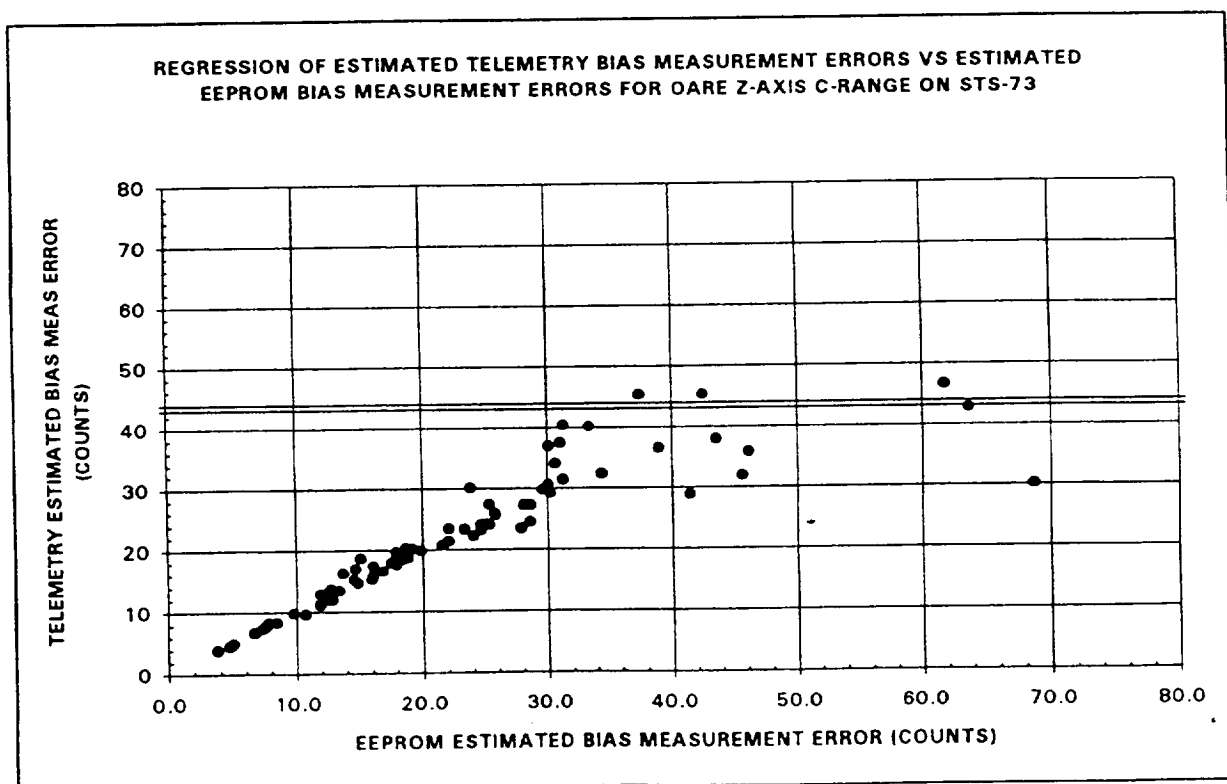


Figure A-13. Comparison of Estimated Bias Errors from Telemetry and EEPROM for same Bias Calibrations for Z-Axis.

A4. BIAS ESTIMATES BASED UPON WEIGHTED LEAST SQUARES FITS

The bias was measured 170 times on STS-73 for each of the three axes on the C-range. Using the methodology discussed above, estimates of the measurement errors associated with each bias measurement were calculated. The results for the OARE X, Y, and Z axes are shown in Figures A-14, A-15, and A-16, respectively. The bias measurements are shown along with their associated error bars.

As can be seen, there is considerable variation of the individual bias measurements, but the variation is generally explained by the measurement errors associated with the bias measurements. There are a few bias measurements which are widely separated from the others. These could be a result of thruster firing during the bias sequence.

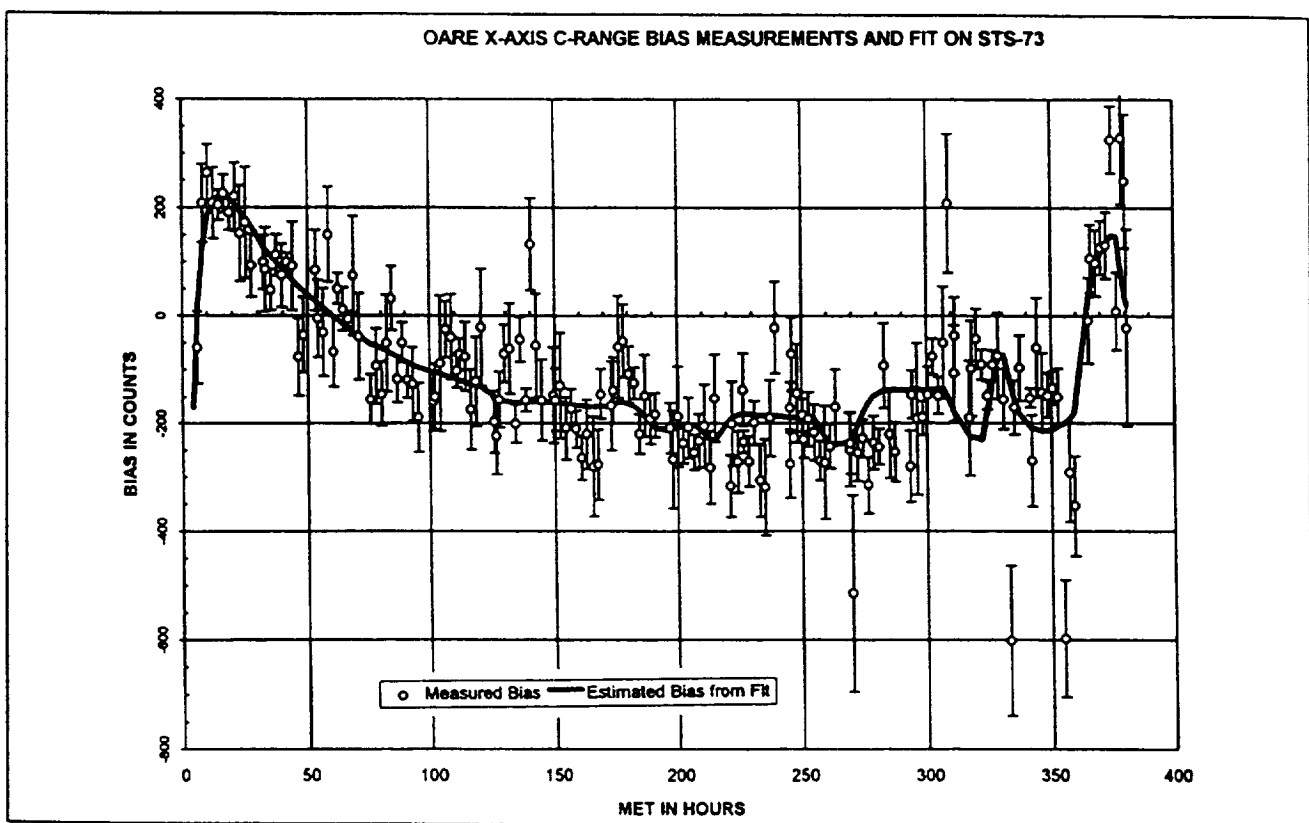


Figure A-14. Bias Measurements and Fit for OARE X-Axis on STS-73.

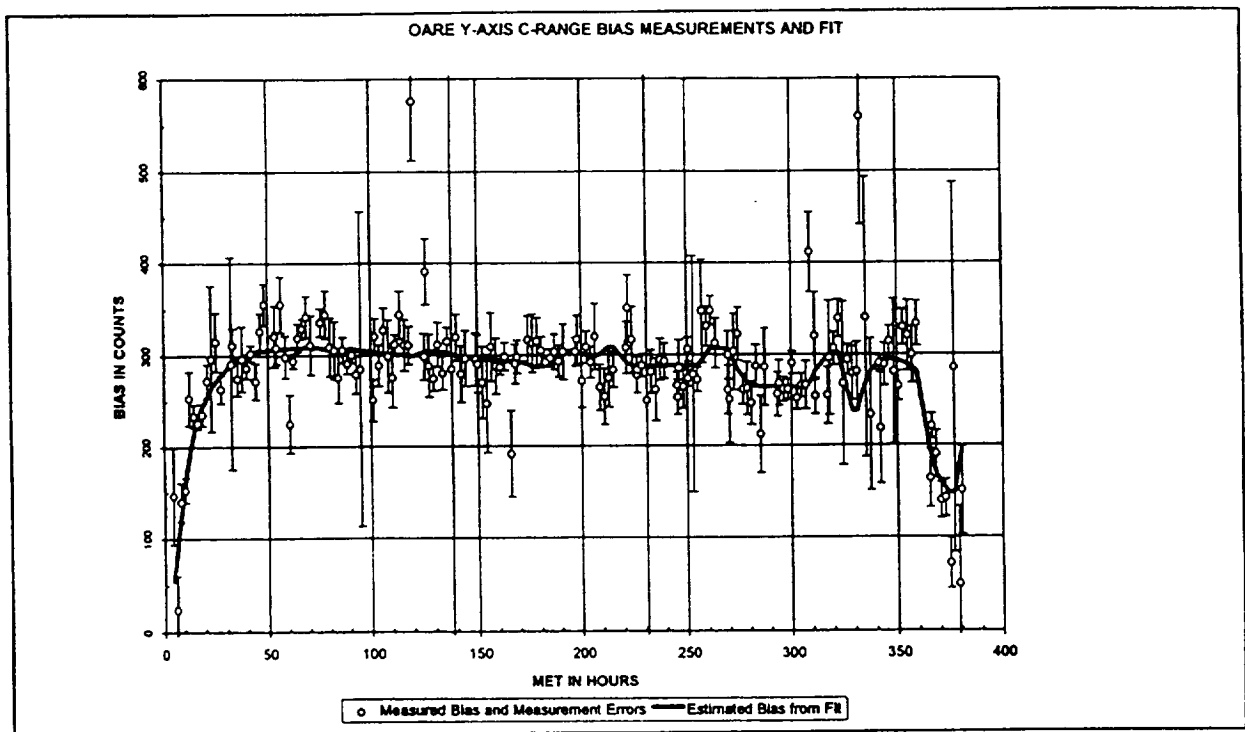


Figure A-15 Bias Measurements and Fit for OARE Y-Axis on C-range.

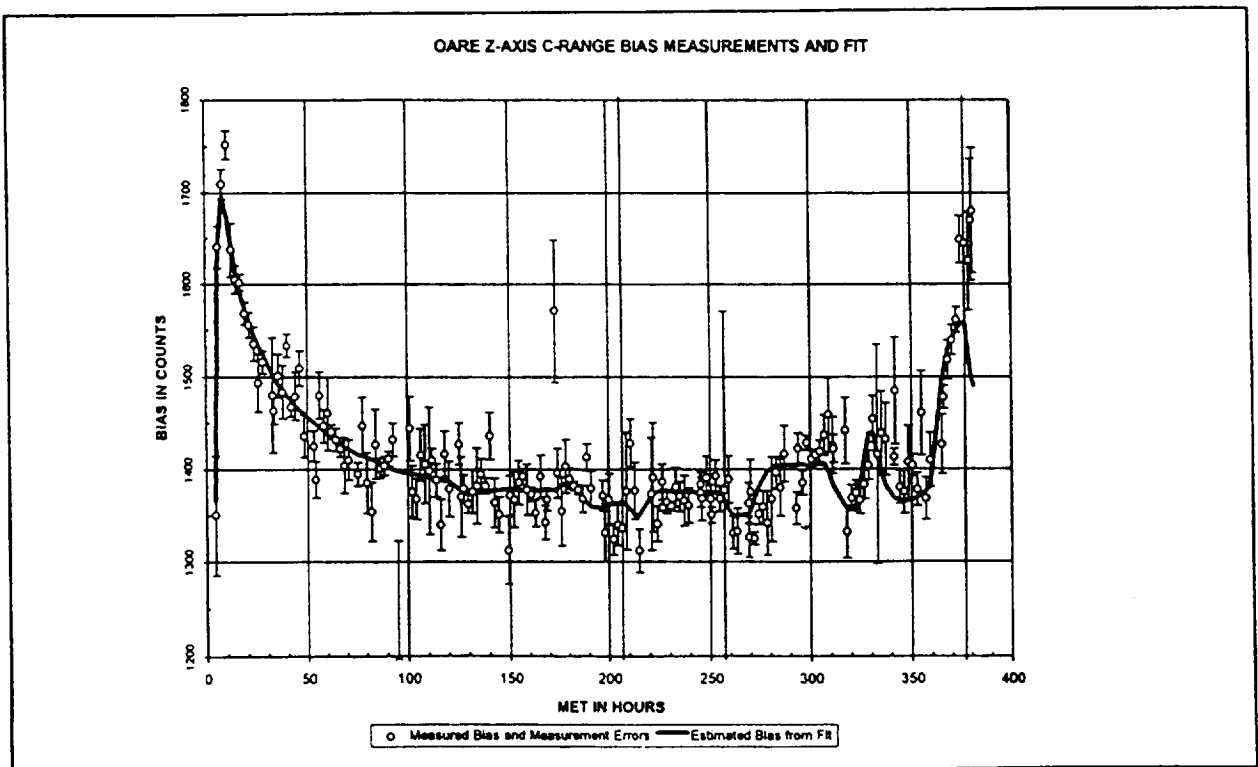


Figure A-16. Bias Measurements and Fit for OARE Z-Axis on C-Range.

The bias can be characterized by an initial transient after launch as a function of time and a small dependence upon temperature. In the same manner as on STS-62 [3], we have fitted the measured bias data with a function of the following form:

$$\text{Bias} = A_1 + A_2 * e^{-(t/t_0)} + A_3 * e^{-(t/t_1)} + A_4 * T \quad (\text{eq. 10}),$$

where A_1 , A_2 , A_3 , A_4 , t_0 and t_1 are fitted coefficients, t is the mission elapsed time in hours, and T is the instrument temperature in degrees Celsius.

A weighted least squares procedure was used to determine the coefficients for the C-range. As part of the fitting procedure, data points (approximately 9 for each axis) which were significantly off the fitted curve, i.e., 2 standard deviation effects, were removed from those included in the fit and the fitting procedure was repeated for the C-range fits. For the B and A ranges, only a standard least squares procedure was used. Results from these fits are shown in Table A-1.

The bias calculated by equation 10 is then used to estimate the actual bias during the mission as a function of MET. This bias is then used to calculate the actual acceleration using equation 1. We believe that the error in the acceleration measurements associated with this bias estimation procedure is about 30-50 nano-Gs. The error could be further reduced if there were more quiet periods during the mission when a low noise bias calibration could be performed.

A5 SCALE FACTOR CALIBRATION

Scale factor measurements are made by applying a known non zero signal to the sensor and electronics for each channel and each range. These measurements may be contaminated by noise in the external environment or by internal noise in several forms.

For OARE, the method of scale factor calibration involves rotating the Motor/Table Subsystem (MTS) (sometimes called "the table") at a known angular rate ω with a fixed sensor to center-of-rotation offset radius r . The known signal is thus the controlled centripetal acceleration. While collecting scale factor data, the sensor also experiences a bias (assumed constant) and is exposed to an external signal. Data collected before and after the scale factor slew assists in removing the bias and external signal effect.

The basic scale factor measurement model is shown in Figure A-16.

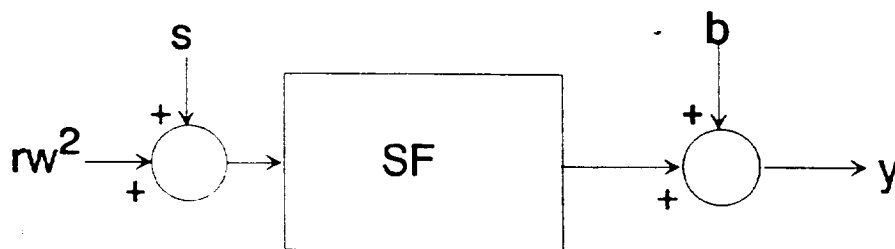


Figure A-16. Scale Factor Measurement Model

Table A-1 STS-73 Bias Fits to EEPROM Data.

STS-73 BIAS FITS TO EEPROM DATA			
OARE X-AXIS			
Range	A	B	C
Fitted Constant A1	12.65	-59.26	-455.45
Fitted Constant A2	-635.22	-4,038.81	-2,022.28
Fitted Constant A3	16.27	47.32	535.46
Fitted Constant A4	0.444	2.348	14.011
Fitted Constant to	1.5	1.5	5.25
Fitted Constant t1	105	87.5	64.3
Standard Deviation of Fitted-Measured	0.87	8.19	74.60
R-Squared of Fit	0.956	0.940	0.832
Number of Measurements	13	13	161
OARE Y-AXIS			
Range	A	B	C
Fitted Constant A1	18.76	53.41	391.38
Fitted Constant A2	-7,462.98	-1,505.90	-254.68
Fitted Constant A3	-1.69	-14.75	157.73
Fitted Constant A4	-0.956	-1.203	-5.662
Fitted Constant to	0.62	0.62	23
Fitted Constant t1	170	500	39.5
Standard Deviation of Fitted-Measured	0.49	2.22	28.81
R-Squared of Fit	0.998	0.965	0.985
Number of Measurements	13	13	160
OARE Z-AXIS			
Range	A	B	C
Fitted Constant A1	162.62	212.35	1,238.89
Fitted Constant A2	-422.83	-979.25	-9,570.69
Fitted Constant A3	24.02	42.82	238.82
Fitted Constant A4	0.316	0.198	7.401
Fitted Constant to	1.42	1.42	1.42
Fitted Constant t1	11.5	20	49
Standard Deviation of Fitted-Measured	0.45	2.46	30.56
R-Squared of Fit	0.973	0.539	0.999
Number of Measurements	13	13	160

From this model, the k^{th} measurement y_k is given by

$$y_k = (r\omega^2 + s_k) / SF_A + b_k \quad (\text{eq. 11}),$$

where s_k is the signal at the k^{th} measurement time and b_k is the internal bias at the k^{th} measurement time. We assume that ω is constant throughout the slew. We also assume that s_k contains two components: (1) an acceleration signal which is fixed with respect to the MTS base throughout the slew and (2) a noise input with zero mean. To eliminate noise, consider averages of the measurements over the data set (with length n)

$$\bar{y} = (r\omega^2 + \frac{1}{n} \sum_{k=1}^n s_k) / SF_A + \bar{b} \quad (\text{eq. 12}),$$

where $(\bar{})$ is the average value of () .

From this equation we can find the actual scale factor SF_A . Here, \bar{y} is the average of the measurements and $r\omega^2$ is known. The remaining unknown, s_k , is a combination of the external signal and noise. This is related to the midpoint measurement (MP). During the slew, the sensor records varying magnitudes of the external signal. The bias and centripetal acceleration, however, remain fixed in magnitude. If the measurements are centered around the midpoint, the midpoint measurement can be used to estimate this external signal and remove it from the scale factor equation. It can be shown that the influence that the external signal and bias have on the scale factor measurements is related to the sinc function $(\sin(x)/x)$ of the angular travel. The actual scale factor can then be found from the following equation:

$$1 / SF_A = \frac{\bar{y} - MP(\sin(\delta) / \delta) - (1 - (\sin(\delta) / \delta))\bar{b}}{r\omega^2} \quad (\text{eq. 13}).$$

The scale factor calibration is $SF_C = SF_A / SF_N$, where SF_N is the nominal scale factor.

Scale factor calibrations were calculated for all three OARE axes and the three ranges. The results are shown in Table A-2.

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13. ABSTRACT (Maximum 200 words) The report is organized into sections representing the phases of work performed in analyzing the STS-73 (USML-2) results. Section 1 briefly outlines the OARE system features, coordinates, and measurement parameters. Section 2 describes the results from STS-73. The mission description, data calibration, and representative data obtained on STS-73 are presented. Also, the anomalous performance of OARE on STS-73 is discussed. Finally, Section 3 presents a discussion of accuracy achieved and achievable with OARE.				
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Table A-2. Scale Factor Correction Factors for STS-65 OARE Axes and Ranges

AXIS	RANGE	VALUE
X	A	1.034
X	B	1.025
X	C	1.028
Y	A	1.119
Y	B	1.123
Y	C	1.099
Z	A	1.096
Z	B	1.114
Z	C	1.090*

*This Scale Factor Correction was computed from the B range measurement.

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